SIMULATION OF LONG TUBE VERTICAL EVAPORATOR

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By
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CERTIFICATE

This is to certify that the present work, "Simulation of long tube vertical Evaporator" has been carried out under my supervison and has not been submitted elsewhere for a degree.

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ABSTRACT

A simulation programme is developed to predict the profiles of liquor temperature, concentration, heat flux, overall heat transfer co-efficient, pressure, pressure gradient, void fraction and vapor quality along the tube length of a natural circulation LTV evaporator. These quantities are predicted for the nonboiling and boiling sections of an evaporator tube from a combination of the following expressions:continuity, momentum and energy balance equations, and frictional pressure drop and holdup correlations for single phase and two phase flow, heat transfer correlation for the nonboiling, nucleate boiling and annular film regions, and correlations for the engineering properties of the process liquor such as thermal conductivity, viscosity, density, surface tension, boiling point rise and specific heat. A stepwise computation procedure has been developed starting with feed inlet conditions assuming a series of differential sections in the nonboiling and boiling sections of the tube and using the criteria of a maximum in liquor temperature profile and a minima in the pressure gradient curve for the transition from nonboiling to nucleate boiling and from nucleate boiling to annular film region respectively.

Results from this simulation programme agree with Badger's experimental data with an overall accuracy of 15% and agreement is within 3% for the temperature profile and an average deviation of 25% for the overall heat transfer co-efficient based on Gudmundson's experimental data for water. The model is applied to bamboo, baggase and pine black liquors over the concentration range 12-28% and the pronounced effect of viscosity

on heat transfer rates is illustrated for the following conditions: Feed-rate 100 tons/hr, temperature 50°C and concentration 12.0%; Evaporator-tube diameter 51 mm, length 7.6 m and number of tubes 300, dirt scale resistance R_D = 0.45 m^2 °K/KW. The nonboiling section length is 0.92 m and 2.13 m for bamboo and bagasse black liquors; the corresponding values of the overall heat transfer coefficient are 2.4-2.7 KW/m^2 °K (from 50°C, 0.9 cp to 106°C, 0.45 cp) and 0.8-1.1 KW/m^2 °K (from 50°C, 4.7 cp to 102.4°C, 1.9 cp) with clean surfaces. In the boiling section the overall heat transfer co-efficient values are 2.4-3.1 KW/m^2 °K and 2.5-3.3 KW/m^2 °K for bamboo and baggase black liquors respectively; the final concentration, temperature and viscosity values are 27.8%, 95.3°C, 1.1 cp for bamboo and 25.9%, 86.2°C, 9.8 cp for bagasse black liquors assuming clean tube surface. With the inclusion of the dirt scale resistance the nonboiling length increases to 1.83 m and 2.75 m with a corresponding decrease in heat transfer co-efficient to 1.2-1.3 KW /m^2 °K and 0.6-0.7 KW/m^2 °K for bamboo and baggase black liquors respectively in the nonboiling section. In the boiling region the dirt resistance decreases heat transfer co-efficient to 1.2-1.4 KW/m^2 °K and 1.2-1.45 KW/m^2 °K for bamboo and baggase black liquors respectively giving a final liquor with concentration, temperature, viscosity of 15.7%, 103°C, 0.41 cp for bamboo and 15.4%, 99°C, 2.0 cp for baggase black liquor.

CHAPTER 1

INTRODUCTION

Natural circulation long tube vertical (LTV) evaporators are widely used for the concentration of solutions such as milk, fruit juice, spent pulping liquors etc. This study deals with the development of a model to predict changes in evaporation capacity and to recommend auxiliary heat exchange equipment that may be needed to accomodate a large change in the viscosity of the process liquor. A good example is the evaporation of weak black liquors from alkaline pulping process. Paper mills in India use bamboo as the major raw material and smaller amounts of mixed hardwoods, salai, bagasse, grasses, pine etc. Increasing quantities of baggase and eucalyptus may also become available to the paper industry. The evaporation plant in a paper mill must be capable of handling bamboo, baggase, eucalyptus black liquors and also mixed black liquors whose viscosities vary considerably over the same range of concentration and temperature[38].

Fluid flow and heat transfer mechanisms in a LTV evaporator result in nonboiling, nucleate boiling and annular film regions along the tube length and determine the changes in solution temperature and concentration. In simulating the performance of a LTV evaporator process feed liquor conditions such as flow rate, temperature, concentration and pressure are usually available. Simulation consists in predicting the profiles of liquor temperature, concentration, heat flux and overall heat transfer co-efficient along the length of the evaporation tube. These computations would also give variation in pressure, pressure gradient, void fraction and vapor quality along the tube length. All these

quantities can be predicted for the given evaporator unit from a combination of the following expressions: Continuity, momentum and energy balance equations, and frictional pressure drop and holdup correlations for single phase and two phase flow, heat transfer correlation for the nonboiling, nucleate boiling and annular film regions, and correlations for the engineering properties of the process liquor such as thermal conductivity, viscosity, density, surface tension boiling point rise and specific heat. Computations would begin with the feed inlet conditions at the bottom of the evaporation tube and proceed through the nonboiling, nucleate boiling and annular film regions, and thus traverse the entire tube length. Computations are carriedout in a stepwise manner assuming a series of differential sections of the evaporator tube and using the criteria of a maximum in liquor temperature profile and a minima in the pressure gradient curve for the transition from nonboiling to nucleate boiling and from nucleate boiling to annular film region respectively.

Simulation programme developed in this study is compared with the experimental results of Brooks and Badger[4] and Gudmundson[2,45] for evaporating water and subsequently used for the concentration of pine, bamboo and baggase black liquors.

CHAPTER 2

Fluid Flow Pattern & Heat Transfer Mechanisms in a Long Tube Vertical Evaporator

LTV evaporators generally consist of 2.5 - 7.5 cm. diameter, 5-10 meter long tubes. Fluid flow patterns and heat transfer mechanisms obtainable for a liquor feed below its saturation temperature are shown in Fig.2.1. The following flow patterns and corresponding heat transfer mechanims are normally observed:

1. Single Phase Liquid Flow (Convective Heat Transfer): Solution is heated to its saturation temperature by convection in the nonboiling section with the cold feed introduced at the bottom of the tube.

2. Bubble Flow (Nucleate Boiling): Superheating of the liquor adjacent to the tube wall occurs to some extent and small bubbles of vapor form on the heat transfer surface and results in a bubble flow pattern as they are released from the surface.

3. Slug Flow (Nucleate Boiling and Convective Heat Transfer): With an increase in number and size, the bubbles coalesce and two phase slug flow commences up the tube. In the beginning heat transfer takes place by nucleate boiling mechanism but with the increase in slug size, heat transfer takes place through liquor film by forced convection mechanism.

4. Annular Film Flow (Forced Convection): The increase in vapor velocity results in a central core of vapor flow and an annular climbing film of liquor and heat is transferred across this liquor film by forced convection.

5. Mist Flow (Forced Convection): With an increase in temperature gradient, dry patches begin to appear on the tube surface and liquid droplets are

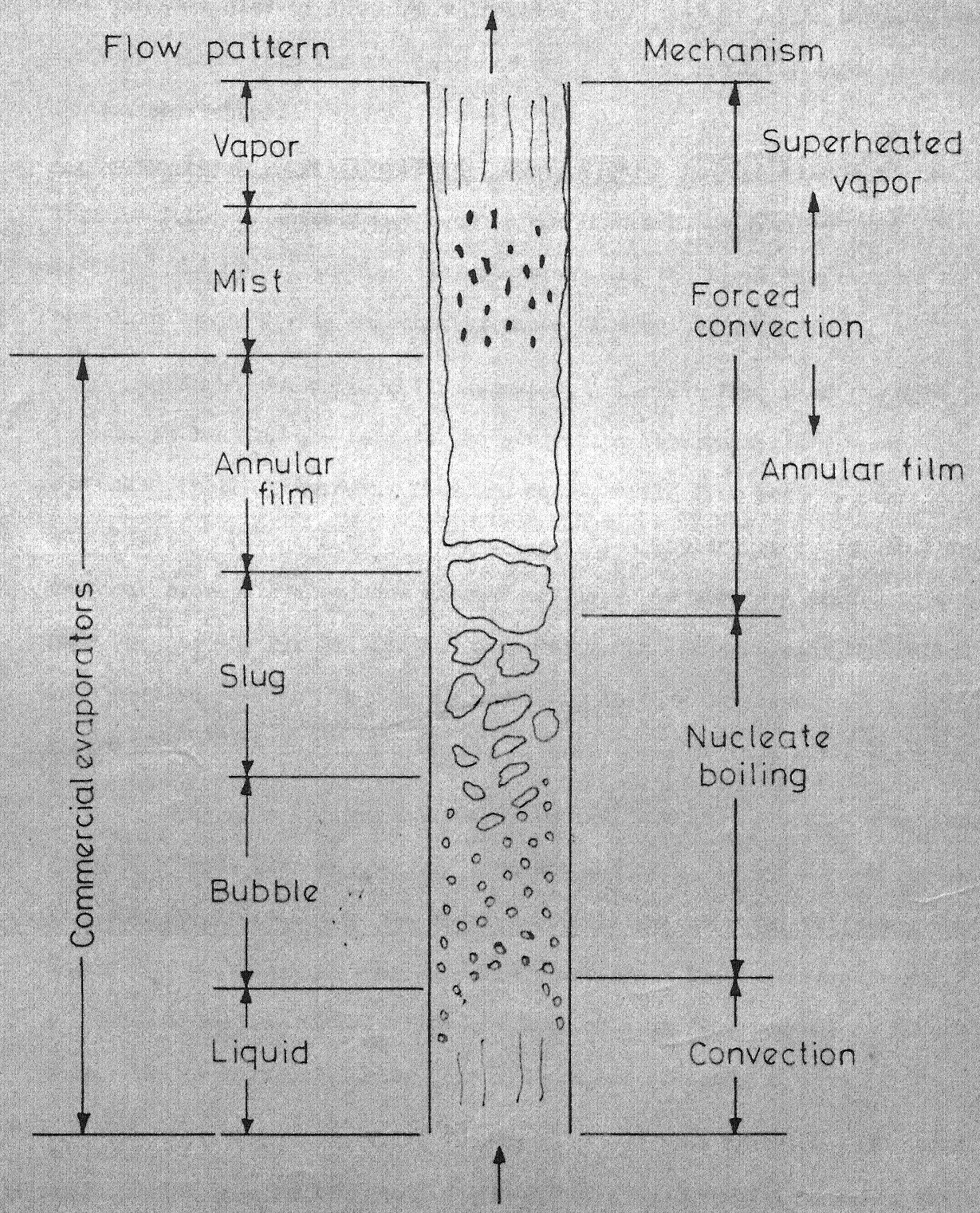

Fig. 2.1 - Fluid flow pattern and heat transfer in a LTV evaporator.

carried as a mist by the high velocity vapor. Heat transfer takes place through liquor film and at places of dry patches, directly to vapor by forced convection.

6. Single Phase Vapor Flow (Forced Convection): As the vapor rate is increased liquor entrainment becomes more and more predominant until, finally, the liquid annulus disappears and all the liquid is carried in the vapor core, giving essentially vapor flow up the tube.

In a commercial LTV evaporator, a certain length of the tube is used in heating the feed to the saturation temperature; in normal operation bubble flow, slug flow and annular film flow regions are encountered. Mist and single phase vapor flow patterns are not usual in chemical process evaporators unless very large temperature gradients are impressed on the system; further evaporation in a single pass is limited to less than 50-60%. Thus it is necessary to consider regions (1) to (4) listed above in a detailed analysis of heat transfer in a LTV evaporator.

The flow regions and the accompanying heat transfer mechanisms, shown in Figure 2.1 are not very distinct and there is considerable overlap in actual operation. For the purpose of this analysis the following heat transfer mechanisms are considered: 1) Convection (nonboiling section) 2) Nucleate boiling (bubble flow and part of slug flow region) 3) Forced convection (remainder of slug flow and annular film region).

Differences in fluid flow pattern and heat transfer mechanisms would result in a variation of the heat transfer co-efficient along the length of the evaporator tube. There is a slight maxima in liquor

temperature caused by pressure drop indicating the start of nucleate boiling region after the nonboiling section. Likewise transition from slug flow to the annular film flow regime is accompanied by a minima in the pressure gradient curve along the tube caused by the high void fraction of vapor (0.8-0.9) which in turn leads to high frictional pressure drop. This has been observed by Anderson et.al.[15] in their experimental findings. These criteria may be used to predict approximately the sections of the tube lengths where single phase liquid flow, bubble & slug flow, and annular film flow regions occur during evaporation. Heat transfer co-efficients in these sections can be predicted using the appropriate available correlations. These are discussed in Chapter 4.

As the liquor traverses up the tube, liquor temperature increases due to sensible heat transfer and pressure decreases as a result of static and frictional forces in the nonboiling section; in this section liquor concentration remains constant as there is no evaporation. Changes in liquor temperature, pressure, pressure gradient and heat flux in a differential length of the nonboiling zone can be predicted by continuity, momentum & energy balance equations; and frictional pressure drop equation for the single phase liquid and heat transfer correlation. The transition to nucleate boiling occurs when the liquor temperature is equal to the saturation temperature corresponding to the pressure at that point in the tube. In the nucleate boiling region two phase flow starts with an increase in the volume of the vapor by evaporation accompanied by an increase in the liquor concentration. A differential length in this region can be considered for predicting the changes in liquor temperature and concentration, pressure,

pressure gradient, quality, void fraction and heat flux by applying continuity, momentum & energy balance equations alongwith void fraction, two phase frictional pressure drop and heat transfer correlations. The stepwise procedure can be repeated until a minima appears in the pressure gradient along the length indicating the start of the annular film flow region. Changes occuring in this section can likewise be predicted by applying continuity, momentum & energy balance equations along with other equations to differential segments of this region in a stepwise manner until the evaporator tube length has been traversed. These stepwise calculation procedures are discussed in Chapter 5.

CHAPTER 3

ENERGY, MOMENTUM & CONTINUITY BALANCES FOR NONBOILING AND BOILING REGIONS

Energy, Momentum & Continuity balance equations are necessary for the simulation of the LTV evaporator. These equations will differ for the nonboiling section (single phase) and boiling section (two phase flow) of the evaporator tube length.

The appropriate balances applicable to the single phase region are discussed first. In the two phase flow regime energy, momentum & continuity balance expressions are obtained for (1) homogeneous model and (2) slip model. The former model assumes that liquor and vapor travel at same velocity where as the latter model is developed on the basis of different velocities for liquor and vapor phases.

A. SINGLE PHASE LIQUID

The following assumptions are made for the one-dimensional analysis of the single-phase flow existing in the nonboiling section of a

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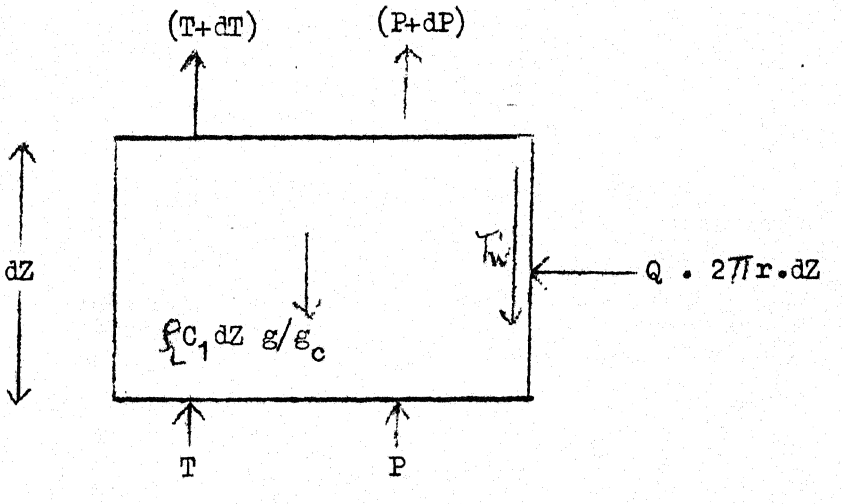


evaporator tube:

1. There is no radial variation of pressure, temperature, velocity & density.
2. Change in the Kinetic Energy is neglegible.

Energy Balance:

Consider a differential section of the nonboiling section (dZ) shown above. Equation (3.1) gives the general differential form of the energy equation.

$$d(\text{Enthalpy}) + d(\text{Kinetic Energy}) + d(\text{Potential Energy}) = dq - dW \qquad (3.1)$$

The terms in equation 3.1 can be evaluated separately as described below.

dH= Enthalpy of mixture leaving differential section

- Enthalpy of mixture enetering differential section

$$= C_L\, dT \quad , \text{ Btu/lb-m} \qquad (3.2)$$

$$\text{Differential change in Kinetic Energy} = 0 \qquad (3.3)$$

$$\text{Differential change in Potential Energy} = \frac{dZ\ g}{J\ g_c} \qquad (3.4)$$

The amount of heat transfered per pound -mass of fluid flowing is given by equation 3.5.

$$dq = \frac{Q \cdot 2\pi r \cdot dZ}{W_L \cdot 3600} \qquad \frac{Q \cdot 2\pi r \cdot dZ}{\rho_L \cdot u \cdot C_1 \cdot 3600} \qquad (3.5)$$

The amount of work done by the system on the surroundings

$$dW_s = 0 \qquad (3.6)$$

Substituing equations 3.2 to 3.6 in equation 3.1, energy equation

gives:

$$dT = \frac{1}{C_L}\left[\frac{Q \cdot 2\pi r \cdot dZ}{C_1 u \rho_L 3600} - \frac{dZ\ g}{J\ g_c}\right] \qquad (3.7)$$

Equation 3.7 can be used to predict the temperature change in a differential section of the nonboiling zone.

Momentum Balance:

Application of Newton's second law of motion to the fluid in the differential section (dZ) gives the momentum balance equation 3.8.

Forces of acceleration - forces of deceleration

= change in momentum of fluid (3.8)

Change in the momentum of fluid is

$$\frac{\rho_L u\ C_1\ (u + du)}{g_c} - \frac{\rho_L u\ C_1\ u}{g_c} = 0 \qquad (3.9)$$

When the equation 3.9 is stated mathematically, it becomes

$$C_1 P - (P + dP)\ C_1 - \frac{g}{g_c}\rho_L\ C_1\ dZ - \tau_w\ \pi\ D\ dZ = 0 \qquad (3.10)$$

Frictional pressure drop and shear stress at wall can be related as

$$\tau_w = \frac{dP_F}{dZ}\ \frac{C_1}{P} = \frac{dP_F}{dZ}\ \frac{D}{4} \qquad (3.11)$$

By using equation 3.11, equation 3.10 can be rewritten as:

$$dP = \frac{-g\ \rho_L\ dZ}{g_c} - \left(\frac{dP_F}{dZ}\right) dZ \qquad (3.12)$$

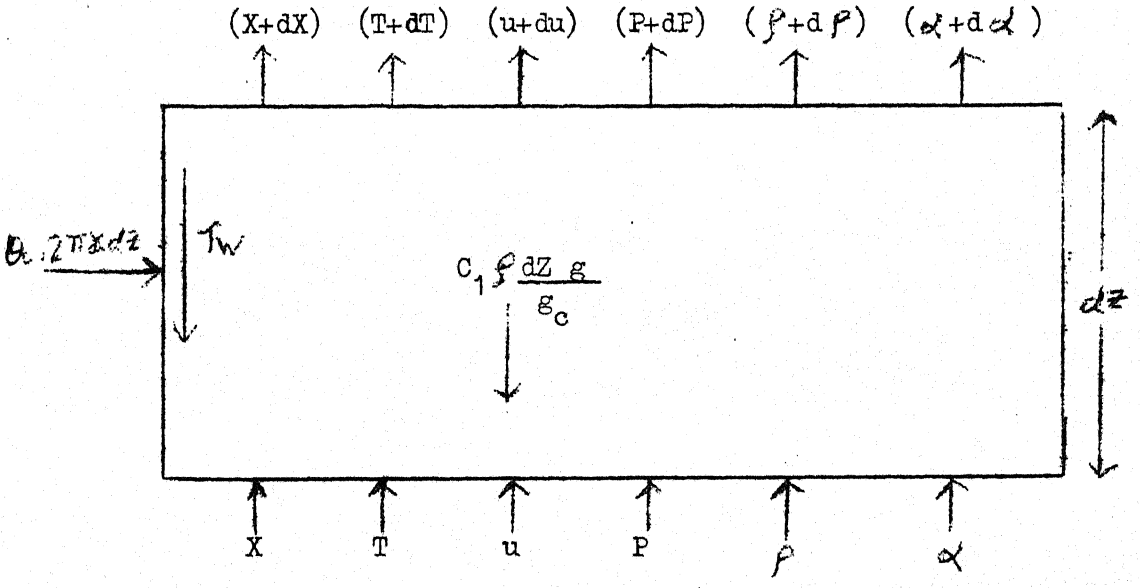
Equation 3.12 can predict the change in pressure along the tube length for the nonboiling section.

B. TWO PHASE FLOW (HOMOGENEOUS MODEL)

For making a one-dimensional analysis of the two-phase flow in the boiling section of an evaporator tube, the following assumptions are made:

1. No radial variation of pressure, temperature, velocity, quality and specific heat (This implies homogeneous vapor liquid mixture).
2. Relative velocity between the vapor and liquid is equal to zero. (no slip occurs between the vapor and liquid).
3. Vapor and liquid are in equilibrium.
4. Density of vapor-liquid mixture is given as

$$\rho = (1-\alpha)\rho_L + \alpha\rho_v$$



Energy Balance:

Consider a differential section of the nonboiling section (dZ) shown above. The general energy equation 3.1 is applied to this differential

section by evaluating each term separately.

dH = Enthalpy of mixture leaving differential section

- Enthalpy of mixture entering differential section (3.13)

The mixture leaving the section with a temperature $(T + dT)$ and a quality $(X + dX)$ had an enthalpy of

$$(1-X-dX)\ C_L\ (T-T_o+dT) + (X+dX)\ \lambda + (X+dX)\ C_p\ (T+dT-T_o)$$
$$= (1-X)\ C_L\ (T-T_o) + (1-X)\ C_L\ dT - (T-T_o)\ C_L\ dX + X\ \lambda$$
$$+ \lambda\ dX + X\ C_p\ (T-T_o) + (T-T_o)\ C_p\ dX \qquad (3.14)$$

The mixture entering the section with a temperature T and a quality X had an enthalpy of

$$(1-X)\ C_L\ (T-T_o) + X\ \lambda + X\ C_p\ (T-T_o) \qquad (3.15)$$

dH can be obtained from equations 3.14 and 3.15, and ignoring second order differentials gives equation 3.16.

$$dH = (1-X)\ C_L + \lambda\ dX + X\ C_p\ dT \qquad (\text{if } T_o = T) \qquad (3.16)$$

The differential change in Kinetic energy (dK.E.) is

$$d(K.E) = \frac{(u+du)^2}{2\ g_c\ J} - \frac{u^2}{2\ g_c\ J}$$
$$\simeq \frac{u\ du}{g_c\ J} \qquad (3.17)$$

The differential change in potential energy (dP.E.)is

$$d(P.E.) = \frac{dZ\ g}{J\ g_c} \qquad (3.18)$$

The amount of heat transfered per pound mass of fluid flowing (dq) is

$$dq = \frac{Q\ .\ 2\ \pi r\ .\ dZ}{3600\ .\ W_L} = \frac{Q\ .\ 2\ \pi r\ .\ dZ}{\rho\ u\ C_1\ .\ 3600} \qquad (3.19)$$

The amount of work (dW_s) done by the system on the surrounding is

$$dW_s = 0 \tag{3.20}$$

Combining equations 3.16 to 3.20 and equation 3.1 gives the energy equation for two-phase flow.

$$(1-X)\ C_L\ dT + \lambda\ dX + X\ C_P\ dT + \frac{u\ du}{g_c J} + \frac{dZ\ g}{J\ g_c} = \frac{Q \cdot 2\pi r \cdot dZ}{\rho\ u\ C_1 \cdot 3600} \tag{3.21}$$

Equation 3.21 can be used to predict temperature change or heat flux in the differential section.

Momentum Balance:

Momentum balance expression represented by equation 3.8 can be applied to the differential section to give equation 3.22.

$$C_1\ P - (P + dP)\ C_1 - \rho\ C_1\ \frac{dZ\ g}{g_c} - \tau_w\ \pi\ D\ dZ = \frac{\rho\ u\ C_1 (u+du)}{g_c} - \frac{\rho\ u\ C_1\ u}{g_c} \tag{3.22}$$

By using equation 3.11, equation 3.22 can be rewritten for pressure drop in the differential section

$$-dP = \frac{\rho\ dZ\ g}{g_c} + \left(\frac{dP_F}{dZ}\right) dZ + \frac{\rho\ u\ du}{g_c} \tag{3.23}$$

Equation 3.23 can be used to predict pressure drop in the differential section.

Continuity Balance:

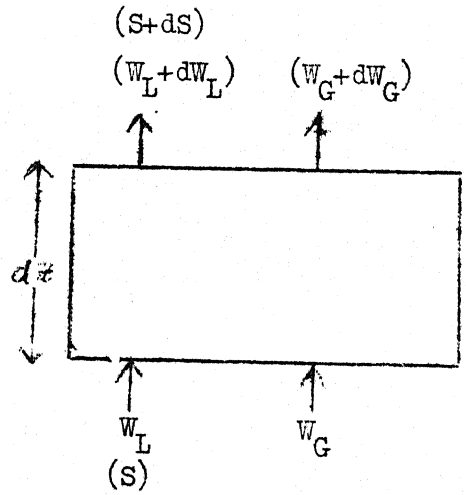
Continutiy equation for the boiling section is represented by equation 3.24.

$$W_T = \rho\ u\ C_1 \tag{3.24}$$

This can be given in differential form for steady flow conditions in the boiling section by equation 3.25

$$u\, d\rho + \rho\, du = 0 \qquad (3.25)$$

Liquor Solid Concentration:



Solids balance for the differential section is given by equation 3.26

Total solid entering = Total solid leaving (3.26)

$$S\,W_L = S\,W_L + S\,dW_L + W_L\,dS + dW_L\,dS \qquad (3.27)$$

Change in liquor concentration over the differential length of the evaporator is given by equation 3.28.

$$dS = \frac{-S\,dW_L}{W_L + dW_L} \qquad (3.28)$$

Mass balance for the evaporation gives

$$dW_L + dW_G = 0 \qquad (3.29)$$

Vapor quality of the mixture leaving the section is

$$X + dX = \frac{W_G + dW_G}{W_L + W_G} = X + \frac{dW_G}{W_L + W_G} \qquad (3.30)$$

Equation 3.29 and 3.30 can be combined to give

$$dW_L = -(W_L + W_G)\, dX \qquad (3.31)$$

By using equation 3.31 and 3.28, equation 3.32 can be obtained to predict the change in liquor concentration over a differential segment of the boiling section of the tube.

$$dS = \frac{S(W_L + W_G)\, dX}{W_L - (W_L + W_G)\, dX} \qquad (3.32)$$

C. TWO PHASE FLOW (SLIP MODEL)

This model differs from the homogeneous model in that there is slip between liquid and vapor which is taken into account by the slip model. The following assumptions are made in the analysis.

1. No radial variation of pressure & temperature.
2. Vapor and liquid are in equilibrium.
3. Density of vapor-liquid mixture is given by

$$\rho = (1 - \alpha)\rho_L + \alpha \rho_v$$

Continuity Balance:

Equation 3.33 can be written for continuity balance

$$W_T = W_L + W_G \qquad (3.33)$$

If the areas of cross section of the two streams are A_L and A_G.

$$W_L = \rho_L v_L A_L \qquad (3.34)$$

$$W_G = \rho_G v_G A_G \qquad (3.35)$$

The mass flux of each stream is then

$$G_L = P_L v_L (1-\alpha) \tag{3.36}$$

$$G_G = P_G v_G \alpha \tag{3.37}$$

By using the definition of vapor quality (X), the above two equations can be used to give alternative expressions for the overall mass flux.

$$G = \rho_L v_L \frac{(1-\alpha)}{(1-X)} = \frac{\rho_G v_G \alpha}{X} \tag{3.38}$$

Momentum Balance:

Many alternative forms of the momentum equation can be derived by manipulating relationships among void fraction, vapor quality, total mass flux, liquor velocity, vapor velocity and other variables. For steady flow in a pipe Wallis[53] has given the following expression.

$$\frac{dP}{dZ} = \frac{-dP_F}{dZ} - \frac{G}{g_c} \frac{d}{dZ}\left[\bar{X} v_L + (1-\bar{X}) v_G\right] + \left[\alpha \rho_G + (1-\alpha)\rho_L\right] \tag{3.39}$$

Combining equation 3.39 with equation 3.38, momentum equation for the differential section can be written

$$\frac{dP}{dZ} = -\frac{dP_F}{dZ} = \frac{G^2}{g_c} \frac{d}{dZ}\left[\frac{(1-X)^2}{(1-\alpha)\rho_L} + \frac{X^2}{\rho_G \alpha}\right] - \left[(1-\alpha)\rho_L + \alpha \rho_G\right] \tag{3.40}$$

Equation 3.40 can be used to estimate pressure drop along the tube.

Energy Balance:

In energy balance, all terms will be alike as in the homogeneous model equation 3.21 except kinetic energy term

$$d\,(K.E) = \frac{1}{g_c J}\, d\left[\frac{X\, v_G^2}{2} + \frac{(1-X)\, v_L^2}{2}\right] \qquad (3.41)$$

Combining equation 3.38 and 3.41, Kinetic energy term becomes.

$$d(K.E) = \frac{1}{g_c J}\, d\left[\frac{G^2 X^3}{2 \rho_G^2 \alpha^2} + \frac{(1-X)^3 G^2}{2 \rho_L (1-\alpha)^2}\right]$$

$$= \frac{G^2}{2 g_c J}\, d\left[\frac{X^3}{\rho_G^2 \alpha^2} + \frac{(1-X)^3}{\rho_L^2 (1-\alpha)^2}\right] \qquad (3.42)$$

Subitituting all terms in equation 3.1, energy equation becomes

$$(1-X)\, C_L\, dT + \lambda\, dX + X\, C_p\, dT + \frac{G^2}{2 g_c J}\, d\left[\frac{X^3}{\rho_G^2 \alpha^2} + \frac{(1-X)^3}{\rho_L^2 (1-\alpha)^2}\right]$$

$$+ \frac{dZ}{J}\,\frac{g}{g_c} = \frac{Q \cdot 2\pi r \cdot dZ}{\rho\, u\, C_1 \cdot 3600} \qquad (3.43)$$

Equation 3.43 can be used for predicting temperature change in the differential section during two phase flow assuming slip model. The change in the liquor concentration for this model will be the same as for the homogeneous model and is given by equation 3.32.

Equation 3.1 to 3.12 are used for the nonboiling section and for the boiling section either equations3.13 to 3.32 assuming homogeneous model for two phase flow or equations 3.32 to 3.43 based on slip model for two phase flow can be used.

CHAPTER 4

REVIEW OF HEAT TRANSFER, PRESSURE DROP AND HOLD-UP CORRELATIONS AND LIQUOR PROPERTIES

Fluid flow patterns and heat transfer mechanisms in a LTV evaporator were discussed earlier in Chapter 2. Changes occur in liquor conditions such as temperature, pressure, pressure gradient, concentration and factors relating to two-phase flow behavior such as quality and void fraction, and associated heat flux and overall heat transfer co-efficient along the length of the evaporator tube. All these quantities are determined in simulating the LTV evaporator. These can be predicted for a given evaporator unit from a combination of the following expressions: continuity, momentum & energy balance equations, and frictional pressure drop and holdup correlations for single phase and two phase flows, heat transfer correlations for the nonboiling, nucleate boiling and annular film regions, and correlations for the engineering properties of the process liquor such as thermal conductivity, viscosity, density, surface tension, boiling point rise and specific heat.

Momentum, energy and continuity relations for one dimensional single phase and two phase flow were discussed in detail in Chapter 3. This chapter deals with the following aspect 1) Critical review of heat transfer correlations for an LTV evaporator and recommended expressions for heat transfer, 2) frictional pressure drop and hold-up correlations to be used in this analysis and 3) Engineering properties for the process liquors.

A. Review of Heat Transfer in a LTV Evaporator:

include convective heat transfer, nucleats boiling and forced convective heat transfer. A summary of the available literature pertaining to these heat transfer mechanisms is given in Table 4.1.

Available heat transfer correlations are summarised separately for each of the three sections - non boiling, nucleate boiling and annular film regions. The complete correlating equations are not given; instead only the major variables that are included in the various investigations of heat transfer in LTV units are given. The tube size, liquor systems, accuracy of predictions and the range of application of these correlations are shown in Table 4.1 for the various expressions proposed by different investigators. It is necessary to choose expressions appropriate for the simulation of this investigation from amongst the various equations in Table 4.1. The use of empirical overall coefficients representing the cumulative effects of heat transfer in the different zones and the steam side characteristics are not suitable for the simulation purposes (Equations in section A, Table 4.1). The liquor flow in the non boiling section of a natural circulation LTV unit is in the laminar flow region for which the non boiling heat transfer correlations proposed by Badger et.al.[6] and Martinelli & Bolter[47] can be used. Both of these expressions give essentially the same value of the non boiling heat transfer coefficient even though the latter include the effect of natural convection in their correlation (Appendix B). For computational purposes it is simpler to use Badger et.al.[6] correlation than Martinelli & Bolter expression; in the latter expression non boiling

Table 4.1 : Summary of Correlations for Heat Transfer in a LTV Evaporator

Tube Size	Liquor System	Heat Transfer Correlation	Remarks
A. Overall Heat Transfer Co-efficient (includes nonboiling and boiling regions)			
1. Uchida & Shinkawa[7]			
L = 2.5 m D = 11.9,18.6,25.5 mm	Water, H_2O-CH_3OH	U = f (λ , Γ , μ , V, F, Pr)	Prediction within ± 15%
2. Gudmundson et.al[2,45]			
L = 10 m D = 51/46 mm	Black Liquor	U=f (p1,p2,p3,p4,p5,C,q)	A least square approach, within ± 15% of original data.
B. Nonboiling Heat Transfer Co-efficient			
1. Sieder & Tate[46]			
L = 1.55 m D = 1.9 cm	Three different oils	h=f (Re,Pr)	Film heat transfer co-efficeint. Re > 2000
2. Martinelli & Boelter[47]			
L = 11.3 -73.5 cm D = 1.06-5.04 cm	Water, oil	h=f(K,F1,G^z,F2,Gr,Pr,X,d_w)	Film heat transfer co-efficent Prediction within ± 20% Laminar range only
3. Badger et.al[6]			
L = 5.62 m D = 3.18 cm	Water, sugar	U_{NB}=f(C_p, ΔT, f , μ)	Over all heat transfer co-efficent. Within ± 20%. Re < 10,000

(Table 4.1 continued)

C. Boiling Heat Transfer Co-efficients (includes nucleate and annular film regions)

1. Brooks & Badger[4]			
L = 6.07 m D = 5.08 cm	Water	$U_B = f(W_f, m, \Delta t_{av}, V)$	Over all co-efficient. Prediction within $\pm$ 20%. Empirical in nature.
2. Stroebe & Badger[5]			
L = 6.07 m D = 5.08 cm	Water, sugar, Duponol solutions	$h_B = f(\rho, C_p, \mu, K, \sigma, \Delta t_L)$	Film heat transfer co-efficient. within $\pm$ 20%. Empirical in nature.
3. Coulson & Mehta[8]			
L = 1.61 m D = 1.27 cm	Water	$h_B = f(\Delta t, W_f, \mu)$	Film co-efficient.
4. Pivet & Isbin[9]			
L = 1.46 m D = 2.54 cm	Water, CCl_4, Isopropyl Alcohol, K_2CO_3 solution	$h = f(d_w, K, U_m, \mu, C_p, \sigma)$	Film heat transfer co-efficient. Empirical equation.
5. Gupta & Holland[17,18]			
L = 2.73 m D = 2.54 cm	Hard water	$U_B = f(\Delta T, \Psi, F, T_b, T_i, C_p)$	Over all heat transfer co-efficient within $\pm$16%

(Table 4.1 continued)

D. Nucleate Boiling Heat Transfer Co-efficient			
1. Mcnelly & Joulson[10]			
L = 1.52 m	Water, Isopropyl Alcohol, Ethyl Alcohol, Cyclohexane	$Nu=f\ (d_w, Pr, Re_L, Re_V, \rho, \mu)$ -low heat flux	Film heat transfer co-efficients.
Various dia. tubes		$Nu=f(Pr, q, d_w, \lambda, \mu_L, P, \sigma, \rho)$ -High heat flux	
2. Guerrieri & Talty[48]			
L = 1.97 m	Cyclohexane, methanol,	$h = f\ (h_c, r_*, \delta)$	Film heat transfer co-efficient.
D = 2.54 cm	Benzene, pentene, heptane		
3. Dengler & Addoms[11]			
L = 6.07 m	Water	$h = f\ (h_L, F, X_{tt})$	Film heat transfer co-efficient for forced circulation vaporization.
D = 2.54 cm.			
E. Annular Film Heat Transfer Co-efficient			
1. Guerrieri & Talty[48]			
L = 1.97 m	Cyclohexane, methanol,	$h_c=f\ (h_L, X_{tt})$	Film heat transfer co-efficient
L = 2.54 cm	benzene, pentene, heptane		

(Table 4.1 continued)

2. Dengler & Addoms[11]			
L = 6.07 m D = 2.54 cm	Water	$h = f(h_L, X_{tt})$	Film heat transfer co-efficient for forced circulation vaporization.
3. Anderson et.al.[14]			
L = 6.07 m D = 2.54 cm	Water	Set of equations	Film heat transfer-coefficient. Prediction within ±20%. theoretical analysis.
4. Lenman & Tait[16]			
L = 1.91 m D = .95-2.54 cm	Water, CH_3OH, C_2H_5OH, Choloroform, 2-propanol, Glycerol	$h = f(C_p, d_w, \rho_L, \sigma, \nu_V, \rho_V)$	Film heat transfer coefficient.
5. Kunze[19]			
Theoretical 'nalysis	-	Set of equations	Film heat transfer coe-efficient. $10^{-3} < Pr < 10^4$

Nomenclature for this table are given below:

λ = liquid thermal conductivity

F = feed rate

p1-p5= adjusted co-efficients

V = vaporization rate

Γ = Mass rate of liquid per unit length of periphery of the evaporator tube length.

C = Correction factor

F1&F2= Factors

W_f = feed rate

v = specific volume of vapor

U_m = log mean liquid vapor velocity

T_b = boiling temperature

q = heat flux

h_c = annular film heat transfer coefficient

h_L = single phase liquid heat transfer coefficient

δ = laminar film thickness

v_V = vapor velocity

Gr = grashof No.

Pe = peclet No.

Gz = graetz No.

X = nonboiling length

ΔT = temperature difference

m = factor

Δt_L = liquid film temperature difference

T_i = inlet temperature

ψ = graphically read function of T

P = pressure

h_f = nucleat boiling heat transfer coefficient

r_* = radius of minimum size thermodynamically stable bubble

X_{tt} = lockhart martinelli parameter

section length is an implicit variable which will require a trial & error procedure for solution.

The heat transfer correlations given (Section C, Table 4.1) represent the boiling heat transfer co-efficient for the combined nucleate boiling and annular film regions and hence cannot be used to predict separately the nucleate boiling & annular film region heat transfer rates.

However, correlations have been proposed for the nucleate boiling region by several investigators (section D, Table 4.1). Guerrieri & Talty[48] correlation requires laminar film thickness which is often difficult to determine from operating units. Correlations proposed by Dengler & Addams[11] applies to forced circulation vaporization only. Mcnelly & Coulson[10] expressions cover a wide range of equipment geometry & liquor systems and includes the effect of all major parameters. These authors have given two correlations for the nucleate boiling region applicable to low heat flux and high heat flux conditions, and can be used to predict heat transfer coefficient.

Heat transfer correlations proposed by various authors for the annular film region are summarised in (Section E, Tabl2 4.1). The prediction based on Guerrieri & Talty[48] correlation is rather poor and Dengler & Addoms[11] correlation is applicable to forced circulation units only. Anderson et.al.[14] theoretical analysis can be used but requires a rigorous computational procedure. Kunz[19] theoretical analysis has not been substantiated by adequate experimental

data. Penman & Tait[16] correlation is based on the use of two dimensionless groups and has been shown to fit very well with their experimental data and compare favourably with the predictions from Anderson et.al.[14] theoretical approach. Hence correlation proposed by Penman & Tait can be used to simulate the heat transfer in the annular film region of a LTV evaporator tube.

A summary of the heat transfer correlations based on the above review for simulating heat transfer phenomena in a LTV evaporator tube is given below:

1. Convective Heat Transfer to Single Phase Liquid (Non boiling Region) - Badger et.al.[6]

$$U_{NB} = 0.06 \left(\frac{C \Delta T_{NB} \rho^2}{\mu_{NB}} \right)^{0.7} \qquad (4.1)$$

U_{NB} = Overall heat transfer coefficient for non boiling section, BTU/hr sq ft. °F

C = Specific heat of liquid, BTU/lb °F

ΔT_{NB} = Mean temperature difference for non boiling section, °F

ρ = Density of liquid, Lb-m/cu.ft.

μ = Viscosity of the liquid lb/ft. hr.

2. Nucleate Boiling Heat Transfer Coefficint- Coulson & Mcnelly[10]

Low heat flux equation:

$$Nu = (1.3 + 39d)\, Pr_L^{0.9}\, Re_L^{0.23}\, Re_V^{0.34} \left(\frac{\rho_L}{\rho_V} \right)^{0.25} \left(\frac{\mu_V}{\mu_L} \right) \qquad (4.2)$$

Where

$$Nu = \frac{h_B d}{k_L} \quad , \quad Pr_L = \frac{C \mu_L}{k_L}$$

$$Re_L = \frac{4 W_f}{d \cdot \mu_L \cdot \pi} \quad , \quad Re_V = \frac{Q \cdot L}{\lambda \cdot \mu_V} = \frac{4 W_V}{\pi d \mu_V}$$

High heat flux equation:

$$\frac{h_B d}{k_L} = 0.225 \left(\frac{C \mu_L}{k_L} \right)^{0.69} \left(\frac{Q \cdot d}{\lambda \cdot \mu_L} \right)^{0.69} \left(\frac{P \cdot d}{\sigma} \right)^{0.31} \left(\frac{\rho_L}{\rho_V} - 1 \right)^{0.33} \quad (4.3)$$

d = Internal dia., ft.

h_B = Nucleate Boiling heat transfer co-efficient, BTU/hr.sq.ft.°F

k_L = Thermal conductivity, BTU/hr ft. °F

C = Specific heat, BTU/lb °F

μ = Viscosity, lb/ft. hr

W_f = Feed rate, lb/hr

Q = Heat flux, BTU/hr sq.ft.

L = Length of the tube, ft.

λ = Latent heat of vaporization, BTU/lb

P = Pressure, lb/sq ft.

ρ = Density, lb/Cu ft.

σ = Surface tension, lb/sq hr

3. Annular film heat transfer coefficient - Penman & Tait[16]

$$\frac{h}{C_{PL}}\sqrt{\frac{D}{\rho_L \sigma g_c}} = 0.012\left[V_v\sqrt{\frac{D\rho_V}{g_c\sigma}}\right]^{0.5} \qquad (4.4)$$

Where

h = film heat transfer co-efficient BTU/Sec. sq.ft. °F

C_{PL} = specific heat of liquor, BTU/lb °F

D = Diameter, ft.

ρ = Density, lb-m/cu ft.

σ = Surface tension, lb-f/ft.

V_v = Velocity of vapour, ft/sec.

g_c = Constant, 32.2 lb-m. ft/lbf. sec^2

4. Shell - Side Heat Transfer Co-efficient-

The shell side heat transfer co-efficient for the filmwise condensation of steam can be determined from equation 4.5 (Mcadams[50])

$$h = 1.13\left[\frac{K_f^3 \rho_f^2 g \Delta H}{L \mu_f (T_{SV} - T_S)}\right]^{0.25} \qquad (4.5)$$

Where

ΔH = Latent heat of condensation, BTU/lb

g = gravitational acceleration, ft/hr^2

L = Length of tube, ft

T_S = Surface temperature, °F

T_{SV} = Saturated vapor temperature, °F

D = Outside diameter of tube, ft.

B. Frictional Pressure Drop & Hold-up Correlations:

Correlations representing frictional pressure drop and hold up are necessary for the prediction of pressure along the length of the evaporator tube length based upon energy, momentum and continuity balances.

Frictional pressure drop in the single phase liquid can be estimated from equations 4.6 - 4.11, given by Knudson & Katz[31].

$$\Delta P_f = \frac{4f}{D} \frac{LV^2 \rho}{2 g_c} \qquad (4.6)$$

The effect of roughness characteristics of the tube on the value of friction factor can be determined from equations 4.7, 4.8 and 4.9.

For laminar flow : $f = 16/N_{Re}$ (4.7)

For turbulent flow: $\frac{1}{\sqrt{f}} = 4 \log \frac{d_w}{e} + 2.28$ (4.8)

for $\frac{r_w/e}{R_e\sqrt{5}} > 0.005$

For transitation flow:

$$\frac{1}{\sqrt{f}} = 4 \log \frac{d_w}{e} + 2.28 - 4 \log \left[1 + 4.67 \frac{d_w/e}{R_e\sqrt{f}} \right] \qquad (4.9)$$

For the case of nonisothermal flow in pipes, there is small change in the value of friction factor as given by Perry[29] and Seider et.al.[30]. In the case of heating

Divide f by $(\mu_a/\mu_w)^{0.38}$ for laminar region (4.10)

Divide f by $(\mu_a/\mu_w)^{0.17}$ for turbulent region (4.11)

(The units to use in equations 4.6 to 4.11 are as follows:

D = Tube Dia., ft

L = Tube length, ft

ρ = Fluid density, lb/Cu ft

V = Fluid velocity, ft/sec.

f = Friction factor

ΔP_f = Pressure drop due to friction lb_f/sq ft.

d_w = Tube dia. inch

r_w = Radius of tube, inch

μ_a = Viscosity at mean temp., cp

μ_w = Viscosity at wall temp., cp)

The prediction of pressure drop in the boiling section would involve a detailed consideration of two-phase liquid-vapor flow patterns. Frictional pressure drop & hold-up correlation for the two phase flow have been reviewed by several authors[21,24,33,34,52-61] and have recommended the use of Lochart & Martinelli[24] correlation for two phase frictional pressure drop given by equation 4.12.

$$\left(\frac{\Delta P}{\Delta L}\right)_{fric} = \left[\frac{2\left(\frac{4}{\pi}\right)^{2-n} C_1 \mu_1^{n} W_1^{2-n}}{D_p^{5-n} \rho_1 g}\right] \chi^{n-2} \left(\frac{D_p}{D_1}\right)^{5-n} \qquad (4.12)$$

The calculation of two phase flow pressure drop by Lochart & Martinelli analysis is discussed in Appendix A.

Levy[62] correlation can be used to prectict the hold-up for

the flow of air water & liquid-vapor mixtures in vertical pipes.

$$\frac{(1-X)^2}{1-\alpha} + \frac{X^2 \rho_L}{\alpha \rho_G} - \frac{(1-X)^2}{2(1-\alpha)^2} = 0 \qquad (4.13)$$

Where X = Quality of vapor

α = Vapor volume fraction

ρ_L = Density of liquid

ρ_G = Density of vapor

C. Engineering Properties of Process Liquors:

The use of momentum, continuity and energy, frictional pressure drop, hold-up & heat transfer correlation for the simulation of long tube vertical evaporator requires a compilation of the engineering properties and charecteristics of commercial process liquors. These properties include density, viscosity, specific heat, thermal conductivity, surface tension, boiling point elevation and vapor pressure data. This study deals with the evaporation of black liquors from alkaline pulping processes. Paper industries in India use bamboo as the main cellulosic raw material. Other fibrous raw materials used in current practice include mixed hard-woods, baggase, grasses, straws, salai and pinewood; the use of these raw materials is rather limited and is determined by their availability to the paper mills. It is hoped that in the next four-five years the use of eucalyptus will be gradually established as a important pulping raw material. Several mills use bamboo as the major raw material and meet the balance of their requirements from same or the other cellulosic raw materials listed above. These raw materials are normally pulped separately owing to diverse differences in their physical,

chemical and morphological properties. The spent liquors from these pulping operations are usually mixed and treated for chemical recovery. The weak black liquor contains 12-22% dissolved solids; approximately two-thirds of the black liquor solids are organic compounds dissolved from the fibrous raw material during alkaline pulping reactions. The remaining one third portion of the black liquor solids constitute the spent inorganic chemicals. The organic compounds include lignin and carbohydrate degradation products, and are dissolved in black liquor as their sodium salts. Other organic compounds include soaps (sodium salt of resin and fatty acids present in the wood). This often leads to foam problems during handling of weak black liquors. The inorganic compounds in the black liquor include residual sodium hydroxide, sodium sulfide, sodium carbonate and smaller amounts of sodium sulfate, sodium thiosulfate, sodium sulfite etc. Black liquors from the pulping of bamboo, baggase and agricultural residues usually contain a appreciable concentration of silica as sodium silicate in solution. This usually leads to scaling problems in chemical recovery equipments requiring frequent shutdowns for maintenance, when the weak black liquor is concentrated to 45-50% solid concentration in multiple LTV evaporators consisting of 5-7 effects. The concentrated black liquor is subsequently burnt in the recovery boilers for reclaiming pulping chemicals and to utilize calorific value of the organic compounds in the black liquor solids.

Even though bamboo is a major raw material in use today, it is possible that substantial quantities of baggase from sugar mill and eucalyptus from plantation may become available to the paper industry. Such a situation would then require that a given pulp mill be in a position

to handle two or more major fibrous raw materials. The chemical recovery units must be capable of handling the black liquors from different fibrous sources. Koorse[38] has demonstrated the diverge differences in some of the engineering properties specially viscosity of bamboo, baggase and eucalyptus black liquors.

We can forsee a condition in the next few years when a particular paper mill will be handling bamboo for five to six months and baggase for the rest of the year. It would be possible to predict the changes in the evaporation plant on switching from bamboo to baggase using the simulation programme of this investigation. This would however require numerous engineering data for bamboo and baggase black liquors. The latter information has been experimentally obtained using commerical bamboo and baggase black liquors from Indian paper mills by Koorse[38]. Correlations for the engineering properties of the liquors are summarized below:

1. Properties of Bamboo Black Liquor - Koorse[38]

Viscosity: $$\mu = \text{Exp}\ (A + B.S + C.S^2 + D.S^3)\ , \text{cp} \qquad (4.14)$$

Where $$A = 4.4014 - 0.2248\ T + 0.0018\ T^2$$

$$B = -0.479 + 0.0296\ T - 0.00025\ T^2$$

$$C = 0.02075 - 0.0013\ T + 0.00001\ T^2$$

$$D = -0.000175 + 0.00015\ T - 0.0000001\ T^2$$

Density: $$\rho_L = 1.0182 + 0.00779\ S - (0.000219 + 0.000003\ S).\ T,\ g/c \qquad (4.15)$$

Thermal Conductivity: $$K = 0.53354269 - 0.003425\ S + (0.0011355 + 0.00000209\ S)T$$

KCal/hr. m°K (4.16)

Boiling point Elevation: B.P.E. = 0.19 S , °C (4.17)

Equation 4.17 for boiling point rise was obtained from limited experimental data and hence needs further refinement with additional data. Nevertheless it can be used as an approximate expression to include the effect of boiling point rise in the evaporator calculations.

2. Properties of Baggase Black Liquor - Koorse[38]

Viscosity: $\mu = \text{Exp}\ (A + B.S + C.S^2)$, cp (4.18)

where $A = 18.276186 - 0.507619\ T + 0.00343\ T^2$

$B = -1.427423 + 0.043054\ T - 0.0003074\ T^2$

$C = 0.032877 - 0.00898\ T + 0.0000064\ T^2$

Density: $\rho_L = 1.0207 + 0.0071\ S - T\ (0.000279 + 0.0000012\ S)$ g/cc (4.19)

Thermal Conductivity: $K = 0.050579 - 0.002563\ S + (0.000899 + 0.00000749)\ S$ KCal/hr.m°K (4.20)

Specific Heat: $C_L = 0.993 - 0.01258\ S + (0.0000556 + 0.000104\ S)$ (4.21)

Boilding Point Elevation: B.P.E. = 0.14 S , °C (4.22)

Equation 4.22 can be used as an approximate expression to include the effect of boiling point rise in the evaporator calculations.

3. Properties of Pinewood Black Liquor - Gudmundson[35]

Viscosity: $\mu = \text{Exp}\ (A + B.S + C.S^2 + D.S^3)$, cp (4.23)

Where $A = 0.4717 - 0.02472\ T + 0.7059 \times 10^{-5}\ T^2$

$B = 0.06973 - 0.5452 \times 10^{-3}\ T + 0.1656 \times 10^{-5}\ T^2$

$C = 0.002046 + 0.3183 \times 10^{-3}\ T - 0.9761 \times 10^{-7}\ T^2$

$D = 0.5793 \times 10^{-4} - 0.6129 \times 10^{-6}\ T + 0.1837 \times 10^{-8}\ T^2$

Density: $\rho_L = 1007 - 0.495\ T + 6.0\ S$, Kg/m^3 (4.24)

Specific Heat: $C_L = (1.0-0.0054\ S)\ 0.4187$, $WS/Kg\ ^\circ K$ (4.25)

4. Properties of Water -

Viscosity: $\mu = 1.996531 - .0160284\ T + .00006745\ T^2$, cp (4.26)

Thermal Conductivity: $K = 587(1+0.00281\ (T-20))\ 2.389 \times 10^{-6}$

Cal/cm.sec. °C (4.27)

5. Vapor Pressure-Temperature Relationship -

Vapor pressure and temperature can be correlated by Antoine equation 4.26 **or** 4.27

$$\log_{10} P = A - \frac{B}{T-B.P.E. +C} \qquad (4.28)$$

$$T = \frac{B}{A - \log_{10} P} - C + B.P.E. \qquad (4.29)$$

Values of Antoine equation constants are given in Table C-1 & C-2 of Appendix C respectively for equation 4.26 and 4.27.

(The units to use in equations 4.14 to 4.27 are as follows

P = Pressure, mm of Hg.

T = Temperature, °C

S = Solid concentration, wt %)

CHAPTER 5

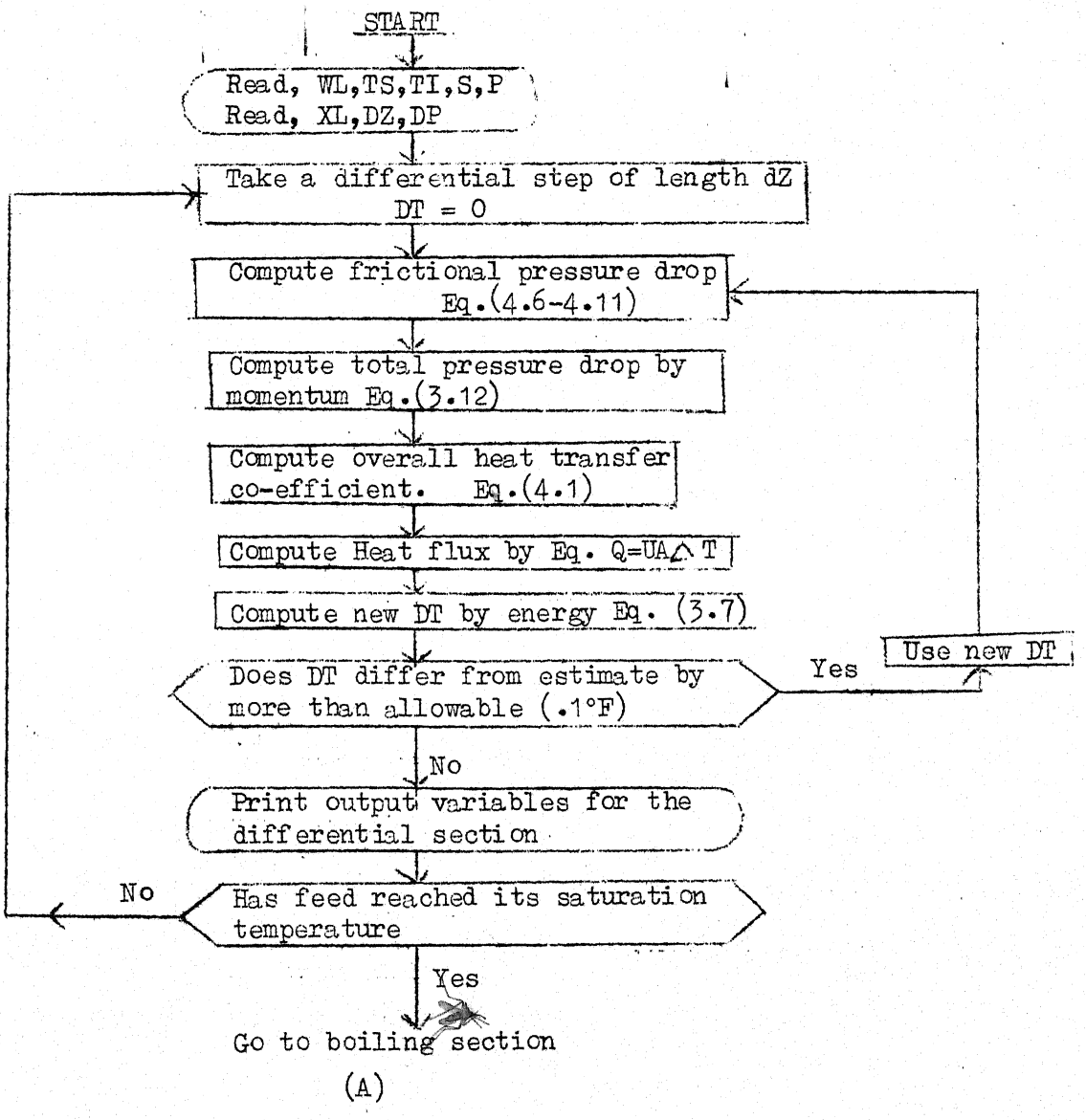
COMPUTATIONAL SCHEME FOR LONG TUBE VERTICAL EVAPORATOR

In simulating the performance of a LTV evaporator, process feed liquor conditions such as liquor flow rate, concentration of solids, temperature and pressures are usually available. Simulation consists in predicting the profiles of liquor temperature, concentration, heat flux and overall heat transfer co-efficient along the length of the evaporator tube. These computations would also give variation in pressure, pressure gradient, void fraction and vapor quality along the tube length. Computations would begin with the feed inlet conditions at the bottom of the evaporator tube and proceed through the nonboiling, nucleate boiling and annular film regions, and thus traverse the entire tube length.

Simulation computations are carried out in a stepwise manner assuming a series of differential sections of the evaporator tube and using the criteria of a maxima in liquor temperature profile and a minima in the pressure gradient curve for the transition from nonboiling to nucleate boiling and from nucleate boiling to annular film region respectively.

For a weak black liquor feed below its saturation temperature, flow chart of computation for the nonboiling section is given in Figure 5.1. Flow rate, concentration, temperature and pressure of feed liquor, steam chest temperature and tube geometry are fixed for starting the calculations. A differential length dZ of tube (.15 meter) is considered to determine the heat transfer rates. The liquor temperature in this differential section is assumed to be isothermal at first. The change in pressure in this section

Fig. 5.1 Flow Diagram for Nonboiling Section of a LTV Tube



can be calculated from the frictional pressure drop correlation equations (4.6 - 4.11) and momentum balance equation.(3.12). The overall heat transfer co-efficient for nonboiling section can be obtained by Badger correlation equation 4.1. Heat flux can be computed by the heat transfer rate equation ($Q = UA\Delta T$). The next step consists of determining differential change in the temperature by energy equation 3.7. This new value of DT is then compared with the previously assumed value for the start of the computations. If they differe by more than a certain specified limit (.1 °F), then the calculations are repeated with this new value of DT. In case the difference is within specified limit then the calculated liquor temperature is compared with the saturation temperature corresponding to the estimated pressure at the exit of the differential section. If the liquor temperature happens to be below the saturation temperature, the calculations are repeated for the next differential section. This iterative procedure is repeated for several differential sections until the liquor temperature equals the saturation temperature of liquor. This point corresponds to the end of the nonboiling regime and subsequent calculations are carried out for the boiling section.

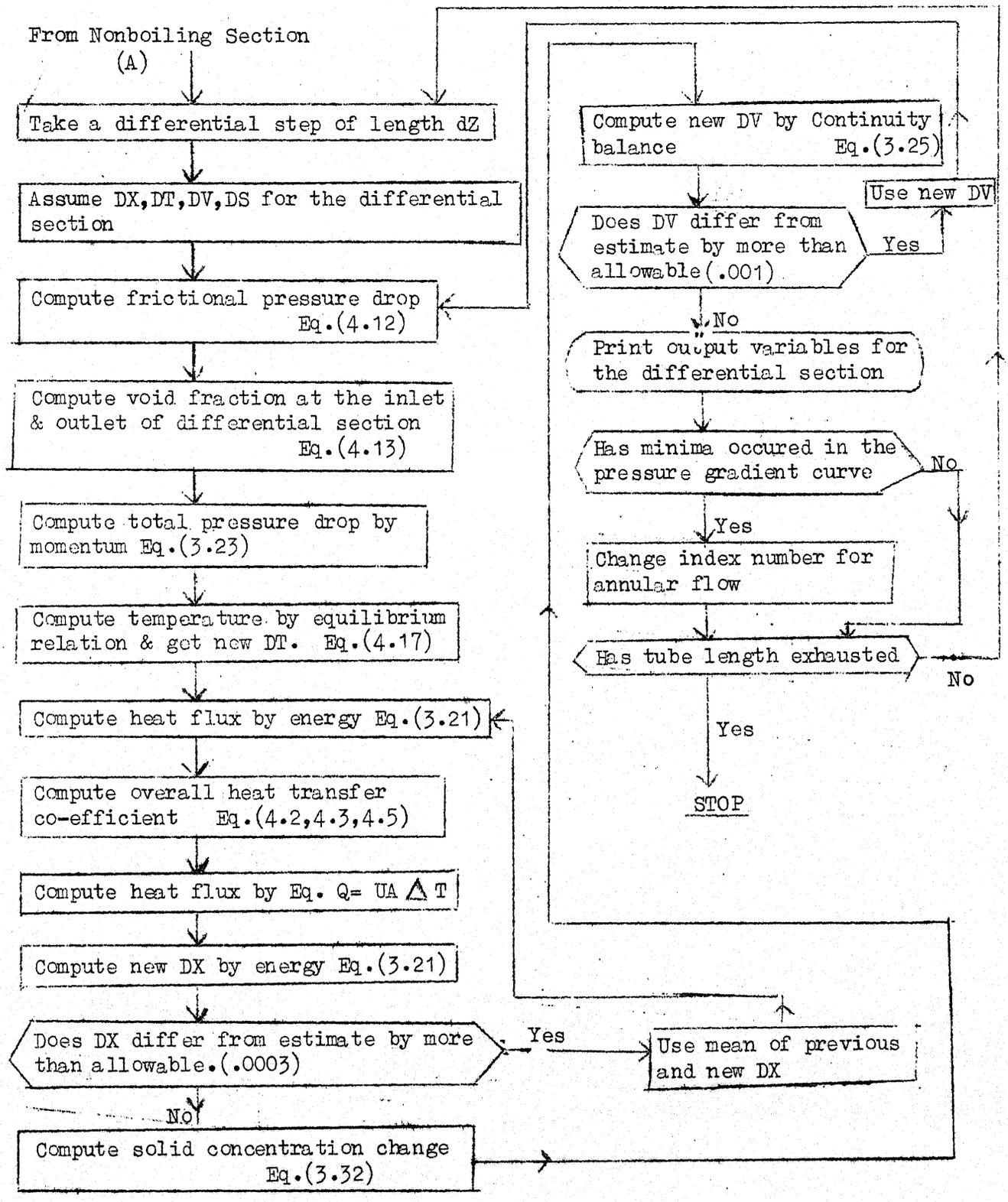
For the boiling section, simulation computations can be performed by assuming either homogeneous model or slip model for the two phase vapor-liquid mixture flow as given below:

1. Homogeneous Model:

Homogeneous model assumes that the velocity of liquid and vapor are same and there is no slip between liquid and vapor. The

computational scheme for estimating changes in the process liquor conditions and heat transfer rate is shown in Fig. 5.2 for the boiling section. Conditions of the liquor feed to the boiling section would be the same as exit liquor conditions from the nonboiling section. Now consider a differential length dZ (0.15 meter) in the evaporator tube length. The calculation for this differential section must give the change in liquor temperature, pressure, pressure gradient, concentration, quality, void fraction, heat flux and overall heat transfer co-efficients. Firstly values for the change in the quality, temperature, solid concentration and velocity (DX,DT,DS,DV respectively) for this differential segment are assumed. Two phase flow frictional pressure drop is calculated by Lockhart and Martinelli correlation (equation 4.12). The void fraction at the inlet and exit of the differential zone can be calculated by Levy correlation (equation 4.13). Obviously the void fraction at the entrance to the boiling section will be zero and gradually increases as boiling progresses along the evaporator tube. The total pressure drop can be obtained by momentum balance(eq.3.23). The temperature corresponding to the calculated pressure can be determined from the Antoinl eq. 4.17 and this would give new value of change in temperature for the differential section. Heat flux for the differential section can be obtained by the energy equation 3.21. Overall heat transfer co-efficients can be calculated by using eq.4.2,4.3 and 4.5. New value of heat flux can be calculated by heat transfer rate equation ($Q = UA\Delta T$). This value of heat flux can be used in energy eq. 3.21 to calculate new value of change in quality for the differential section and is compared with the previously assumed value of DX. If the difference between these two values of DX is

Fig. 5.2 Flow Diagram for Boiling Section (Homogeneous Model) of a LTV Tube



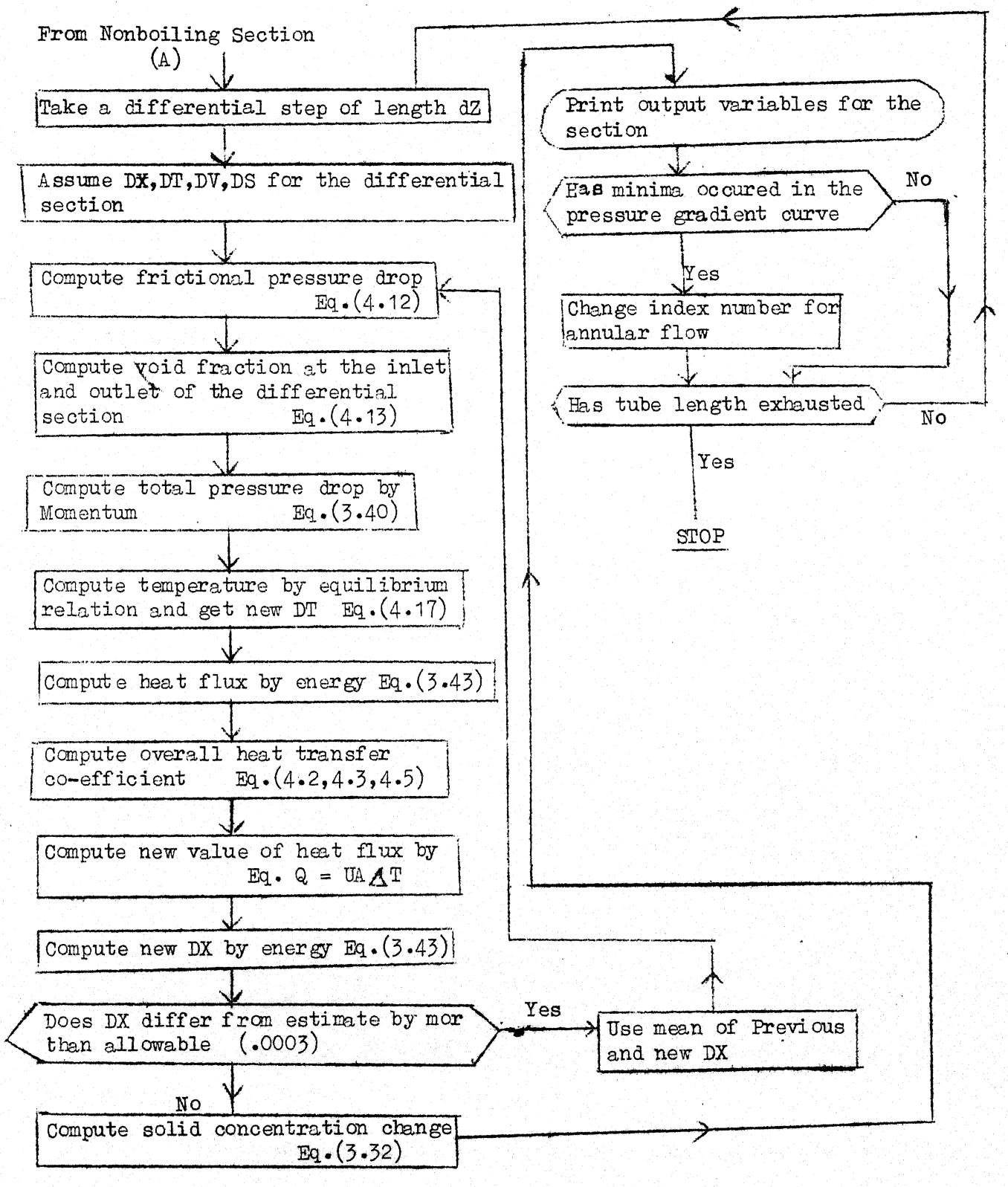
larger than a certain specified limit (.0003) then an average of these two values of quality is used and the calculations are repeated from the step computing heat flux from energy eq. 3.21 until the difference between calculated and the assumed values of DX is within specified limit. In case difference is within specified limit, solid concentration change is obtained by eq. 3.32. Now value of change in the velocity of homogeneous phase can be calculated by continuity eq. 3.25 and can be compared with the previously assumed values of DV. If the difference between these two values is larger than a certain specified limit(.0003 meter/sec) than calculations are repeated with this new value. In case difference is within specified limit, pressure gradient curve is checked for the minima. Index number which will make change from nucleate boiling to annular film flow will be changed with the occurence of minima in the pressure gradient curve. This iterative procedure is carried out for several differential sections until whole of the length is traversed.

For annular flow region, computational procedure is same as for nucleate boiling region except Penman and Tait eq. 4.4 of annular film heat transfer co-efficient is used in place of eq. 4.2 & 4.3.

Slip Model:

Slip model implies a different velocity for liquor and vapor phases. Flow chart for the simulation of heat transfer and other phenomena based on slip model is given in Fig.5.3. This scheme of computation based on slip model is essentially the same as for homogeneous model except with a slight difference that eq. 3.40 and 3.43 are used to estimate pressure drop and temperature change respectively for the differential section.

Fig. 5.3 Flow Diagram for Boiling Section(Slip Model) of a LTV Tube



CHAPTER 6

RESULTS & DISCUSSION

The computational scheme outlined in chapter 5 is used to simulate the long tube vertical evaporator for the following liquor systems: water, bamboo black liquor, baggase black liquor and pinewood black liquor.

Single Effect LTV Evaporation Simulation:

A. Application of Simulation Models to Badger's Data for Water:

The accuracy of the simulation programme for single effect evaporator calculations has been compared with the experimental data of Brooks and Badges[4] for the evaporation of water in a LTV unit consisting 6.1 meter long and 5.08/4.45 Cm diameter tube. Brooks and Badges's experimental data for water are summarized in Table 6.1. The variation in process variables along the tube length is determined by the simulation programme based on flow charts Fig. 5.1 and Fig.5.2 for nonboiling and boiling section (Homogeneous model) respectively. The length of the boiling section and the corresponding rates of evaporation and heat transfer, and the average overall boiling heat transfer co-efficient ($Avg\ U = \sum U_i \triangle T_i \Big/ \sum \triangle T_i$) obtained from the simulation programme given in Table 6.2 for the experiments reported by Brooks and Badger. Brooks and Badger's results are also included in Table 6.2 for comparison purposes. The range and average percent deviation

Table 6.1-Badger's Experimental Data for the Evaporation of Water in LTV Unit

Data	Feed rate (Kg/hr)	Feed inlet (°C)	Steam temp. (°C)	Boiling length (Meter)	Evaporation rate (Kg/hr)	Heat transfer rate in the boiling section (KW)	Average overall heat transfer co-efficient in boiling section ($KW/m^2°K$)
1	107.2	72.1	99.0	5.65	75.0	47.80	3.26
2	108.0	50.1	79.5	5.19	43.4	27.62	3.45
3	120.2	60.0	76.0	5.25	38.8	24.40	3.57
4	112.1	62.0	96.0	5.48	73.4	47.55	3.49
5	113.6	38.0	75.0	4.45	29.3	18.10	3.13
6	121.0	38.5	82.0	4.91	59.5	37.50	3.34
7	111.4	51.0	81.0	5.12	54.6	34.66	3.25
8	112.8	60.0	81.0	5.45	56.5	35.60	3.24

L = 6.1 meter

D = 5.08/4.45 Cm.

Table 6.2 - Simulation Results for Water Evaporation Using Homogeneous Model

Data		Boiling Section Length (meter)	Evaporation Rate (Kg/hr)	Heat Transfer rate in the boiling Section(KW)	Average overall Heat transfer Co-efficient in Boiling Section ($KW/m^2°K$)
	Computed value	4.84	39.6	24.20	3.04
1	Experimental value	5.65	75.0	47.80	3.26
	% Deviation	-14.3	-47.2	-49.5	-7.1
	Computed value	4.21	73.2	20.13	3.16
2	Experimental value	5.19	43.4	27.62	3.45
	% Deviation	-18.8	69.5	-26.6	-8.7
	Computed value	4.28	52.8	17.62	3.07
3	Experimental value	5.25	38.8	24.40	3.57
	% Deviation	- 18.6	37.8	-28.6	-10.8
	Computed value	4.67	105.8	26.00	3.07
4	Experimental value	5.48	73.4	47.55	3.49
	% Deviation	-15.0	43.8	-45.0	-11.9
	Computed value	3.59	58.6	16.90	3.14
5	Experimental value	5.45	29.3	18.10	3.13
	% Deviation	-19.6	101.0	-5.0	0.5

(Table 6.2 continued)

	Computed value	4.04	91.5	22.94	3.15
6	Experimental value	4.91	59.5	37.50	3.34
	% Deviation	-19.5	54.0	-39.1	-5.6
	Computed value	4.25	79.5	21.44	3.17
7	Experimental value	5.12	54.6	34.66	3.25
	% Deviation	-17.1	46.5	-38.3	-2.54
	Computed Value	4.58	74.2	21.70	3.14
8	Experimental value	5.45	56.5	35.60	3.24
	% Deviation	-16.2	32.0	-39.8	-2.8
	Deviation range %	14-20	32-101	5-50	0.5-12
	% Average Deviation	17.2	53.9	33.9	6.2

of the calculated values from the Brooks and Badger's experimental observations are given below (assuming homogeneous model for the boiling section):

Process Variables	Deviation range, %	Average Deviation , %
Boiling section length	14-20	17
Evaporation rate	32-101	54
Heat Transfer rate	5-50	34
Boiling average overall heat transfer co-efficient	2-12	6

The above results show that while this simulation model can predict the overall heat transfer co-efficient quite well, accuracy for predicting the boiling length can be considered moderate and the estimates of the rate of evaporation and heat transfer by the model are poor. The rather large deviations observed may be attributed to the limitations imposed by the homogenous model which assumes equal velocity for the gas and liquid phases during two phase flow.

The slip model for the boiling section was then used to simulate the process conditions of Brook & Badger's experiments based on flow chart 5.1 & 5.3. Results as obtained by using this model and Badger's experimental results are given in Table 6.3 which also include % deviation of the predicted values from the experimental values. The following observations can be made from the results in Table 6.3, concerning the accuracy of the simulation programme based on slip model for two phase

Table 6.3 Simulation results for Water Evaporation Using Slip Model:

Data		Boiling Section Length (Meter)	Evaporation Rate (Kg/hr)	Heat Transfer rate in the boiling Section(KW)	Average overall Heat transfer Co-efficient in Boiling Section ($KW/m^2°K$)
	Computed value	5.42	68.3	43.90	2.68
1	Experimental value	5.65	75.0	47.80	3.26
	% Deviation	-4.1	-8.5	-8.6	-17.5
	Computed value	4.21	40.0	25.77	2.76
2	Experimental value	5.19	43.4	27.62	3.45
	% Deviation	-18.8	-7.6	-6.8	-20.0
	Computed value	4.28	35.0	23.00	2.78
3	Experimental value	5.25	38.8	24.40	3.57
	% Deviation	-18.6	-9.4	-6.9	-21.0
	Computed value	4.99	66.5	42.40	2.71
4	Experimental value	4.58	73.4	47.55	3.49
	% Deviation	-7.3	-8.9	-11.1	-22.2
	Computed value	3.59	33.4	21.20	2.76
5	Experimental value	5.45	29.3	18.10	3.13
	% Deviation	-19.6	14.8	16.4	-11.6

(Table 6.3 continued)

	Computed value	4.04	48.8	30.94	2.72
6	Experimental value	4.91	59.5	37.50	3.34
	% Deviation	-19.5	-17.5	-18.0	-18.3
	Computed Value	4.25	44.1	28.40	2.79
7	Experimental value	5.12	54.6	34.66	3.25
	% Deviation	-17.1	-18.9	-16.9	-14.1
	Computed value	4.58	46.0	28.95	2.78
8	Experimental value	5.45	56.5	35.60	3.24
	% Deviation	-16.2	-18.4	-20.2	-14.2
	Deviation range %	4- 20	8- 19	6- 2'	10- 22
	% Average Deviation	15. 2	13.2	13.1	17.2

flow:

Process Variables	Deviation range, %	Average Deviation, %
Boiling section length	4 - 20	15.2
Evaporation rate	8 - 19	13.2
Heat Transfer rate	6 - 20	13.1
Boiling average overall heat transfer co-efficient	10 - 22	17.2

The above results show that the simulation programme of this study assuming slip model can predict Brooks and Badger's experimental conditions with an overall accuracy of about 15%. Hence the simulation programme based on flow charts 5.1 and 5.3 for the nonboiling and boiling section (slip model for two phas e flow) respectively can be used for the subsequent calculations of this investigation for evaporation of bamboo, baggase and pinewood black liquor from alkaline pulping processes.

B. Comparison with Gudmundson's Experimental curves:

The simulation programme is also used for comparing the predicted values with the experimental results of Gudmundson[2,45]. The evaporator used in the latter work consisted of four 10 m long stainless steel tubes with diameters of 51/46 mm. Gudmundson's results for water at a feed rate of 18 18 Kg/Sm^2 are used in this comparison.

Figures 6.1, 6.2 and 6.3 give the predicted temperature profile and overall heat transfer Co-efficient along the tubelength for the various inlet feed temperatures of 76°C, 81.5°C and 85°C; and corresponding steam temperatures of 91.5°C, 95°C and 86.5°C. The simulation calculations are represented by the continuous curves in the above figures assuming slip model for the two phase flow region. The predicted temperature

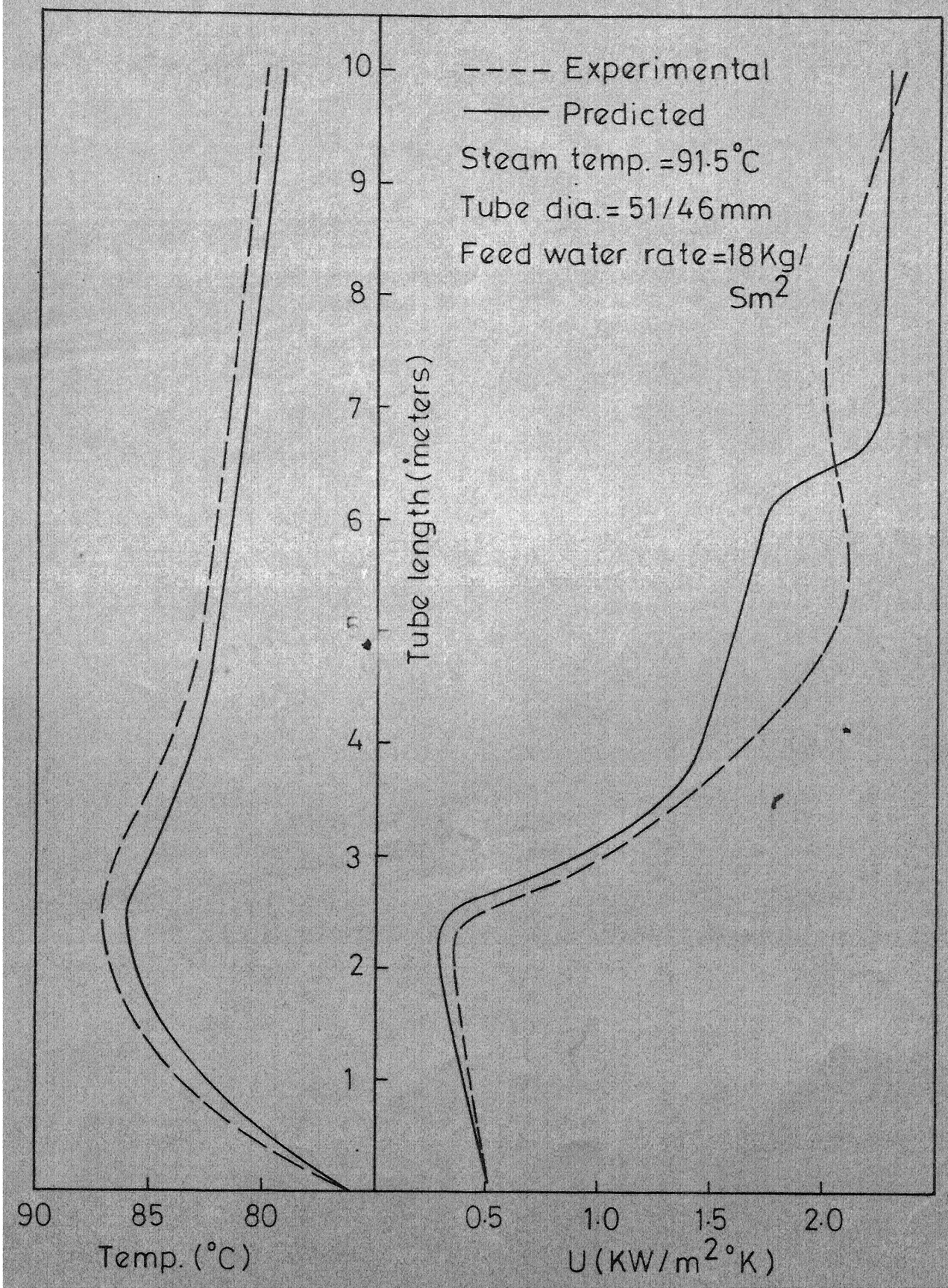


Fig.6.1 - Comparison of predicted values with Gudmundson's experimental data for water.

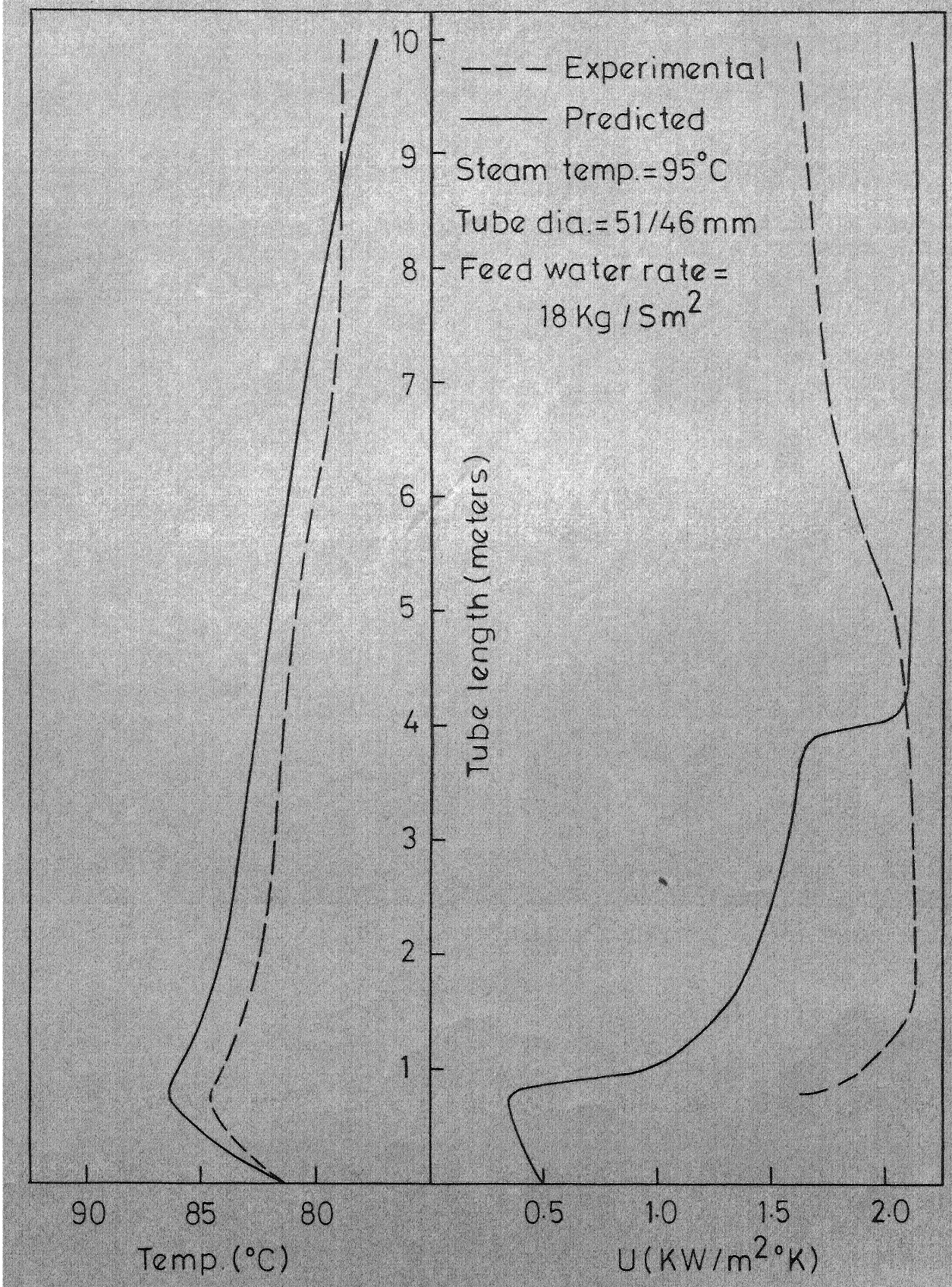


Fig.6.2 - Comparison of predicted values with Gudmundson's experimental data for water.

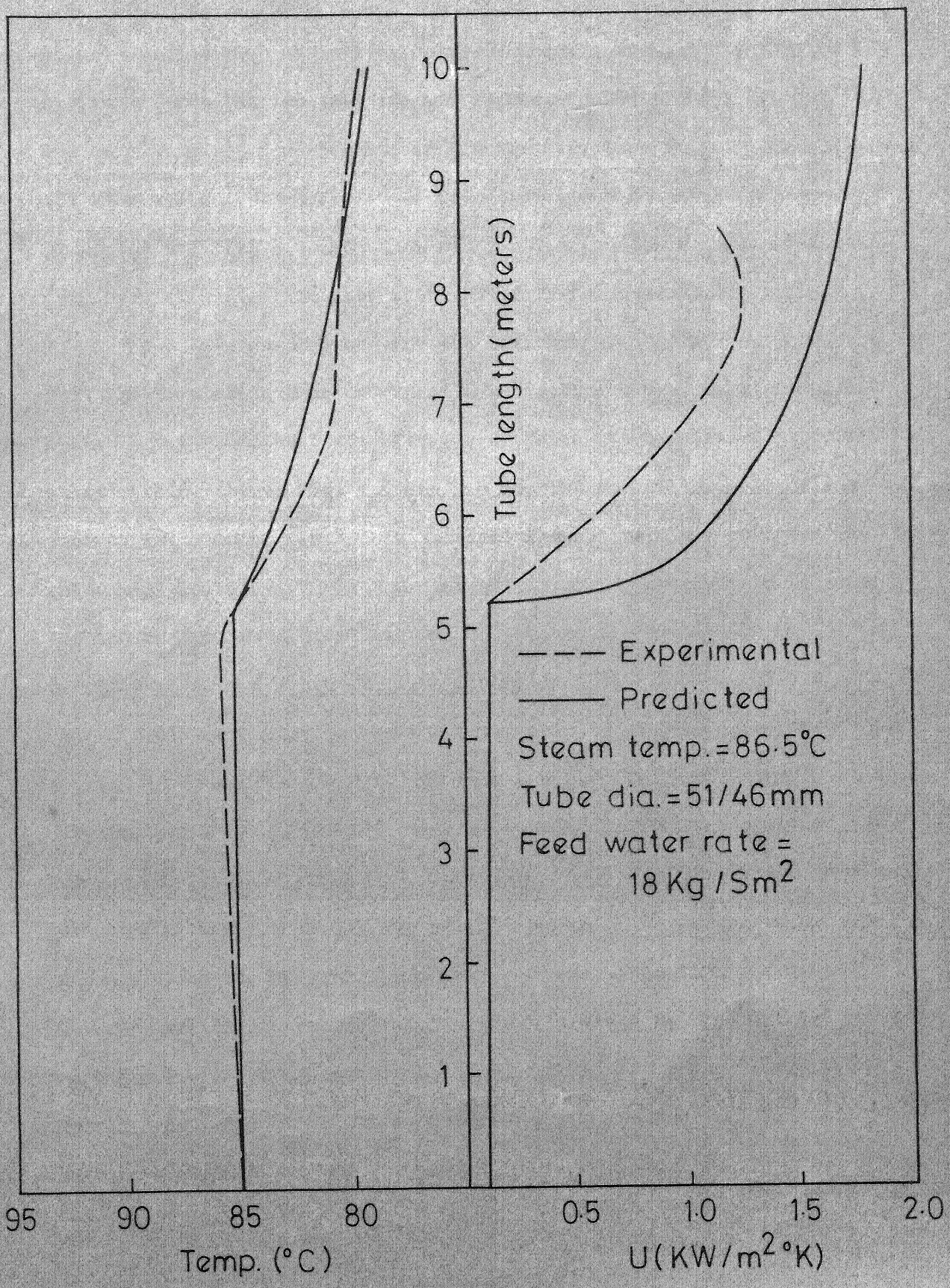


Fig. 6.3 - Comparison of predicted values with Gudmundson's experimental data for water.

profiles agree with the experimental data quite well; the agreement is within 1°C for the two sets of data represented in figures 6.1 and 6.3 and is within 2°C for the data in Figures 6.2. Experimental curves for the over all heat transfer co-efficient diviates somewhat from the predicted profiles based on this study. Experimental results in general show an average deviation of about 25% from the predicted results.

The above comparisons for the heat transfer of LTV evaporator show that the simulation model of this investigation can be used to predict reliable values of heat transfer rates. Hence the simulation programme based on flow charts Fig. 5.1 and 5.3 for the nonboiling and boiling section (slip model for two phase flow) respectively are used for the subsequent calculations of this investigation for evaporation of bamboo, baggase and pinewood black liquors.

C. Evaporation of Pinewood Black Liquor:

Weak black liquor from the Kraft pulping of pine is assumed to contain 12.0% dissolved solids with a flow rate of 100 tons/hr at a temperature of 50°C. The LTV evaporator unit is arbitrarily assumed to consist of 300 tubes, 5.08/ 4.45.cm dia. and 7.6 meters long. Steam chest pressure is taken to be 306 KN/sq.m. Pressure of the liquor feed is assumed to be 104 KN/sq m. A print out of the simulation programme for the evaporation of pinewood black liquor is given in Appendix D-1 for the respresentation of homogenous model describing two phase flow pattern. Physical property correlations reported by Cudmundson[35] are used in this analysis.

The simulation programme gives the output variables in the following order- vapor quality, void fraction, pressure gradient, pressure, temperature, heat flux, overall heat transfer co-efficient and solid concentration. The variations of these variables along the length of the evaporator tube are shown in Fig. 6.4 - 6.11 respectively. It can be observed that of the total length of the evaporator tube (7.6 meter), about 2 meter is used in raising the feed liquor to its boiling point in the non-boiling region.

Fig. 6.4 shows the variation in vapor quality (mass fraction of vapor in the total vapor -liquid mixture flow) along the tube length. It can be seen that the mass fraction of vapor increases from zero at the start of the boiling section to 0.35 and 0.22 towards the end of tube assuming homogeneous and slip models respectively. The difference observed between the two models in caused by the contribution of the kinetic energy terms (eq.3.43). In the homogeneous model kinetic energy is based on the use of homogenecus phase velocity whereas the slip model takes into account the contribution to kinetic energy as terms representing vapor and liquid velocities during two phase flow.

Fig. 6.5 gives the changes in void fraction along the tube and it can be seen that the start of nucleate boiling section is accompained by a steep increase in void fraction caused by rapid rate of nucleation and bubble coalescence. The homogeneous and slip models give essentially the same value for void fraction. Void fraction at the end

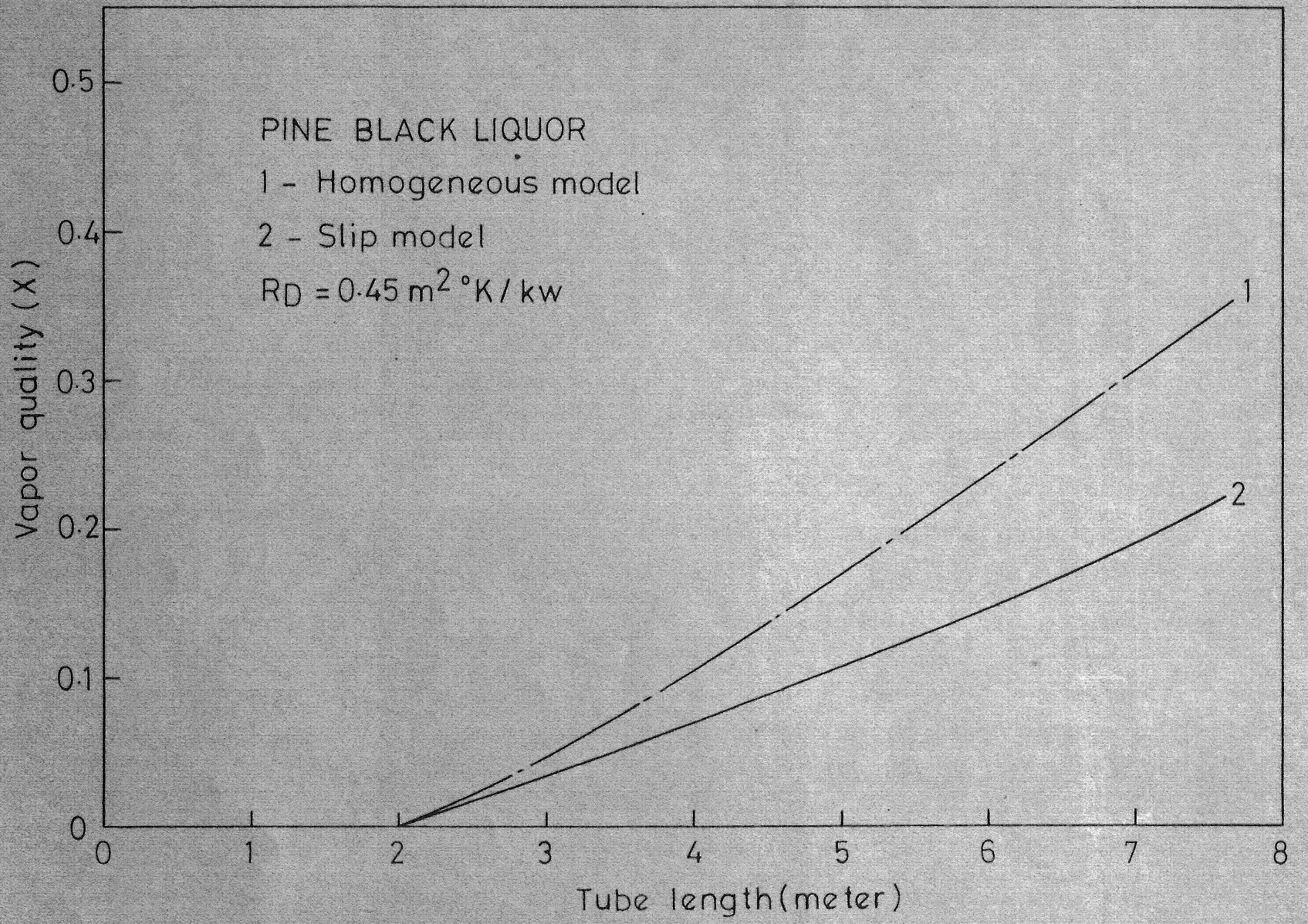


Fig. 6.4- Variation of vapor quality along tube length.

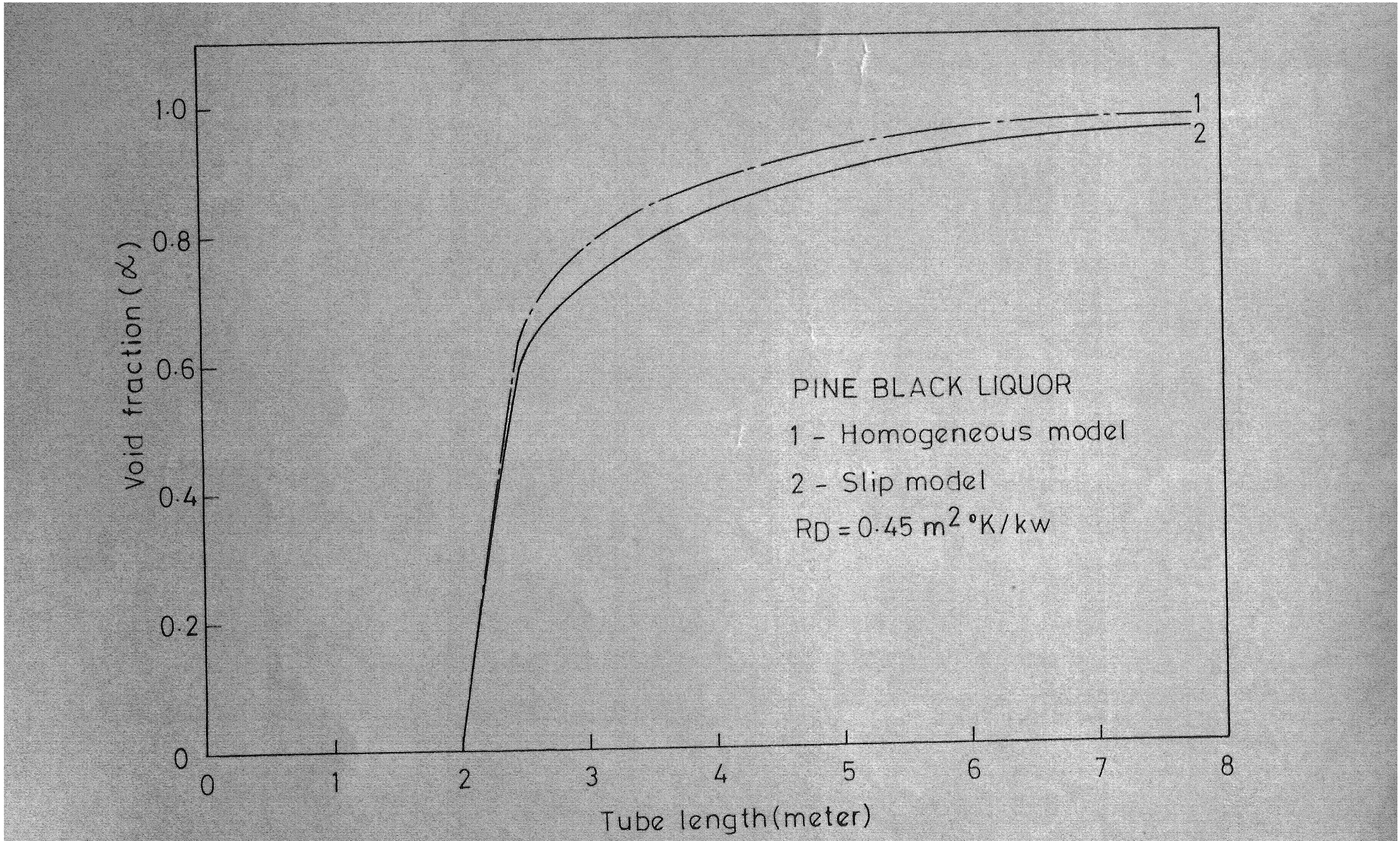


Fig. 6.5 - Variation of void fraction along tube length.

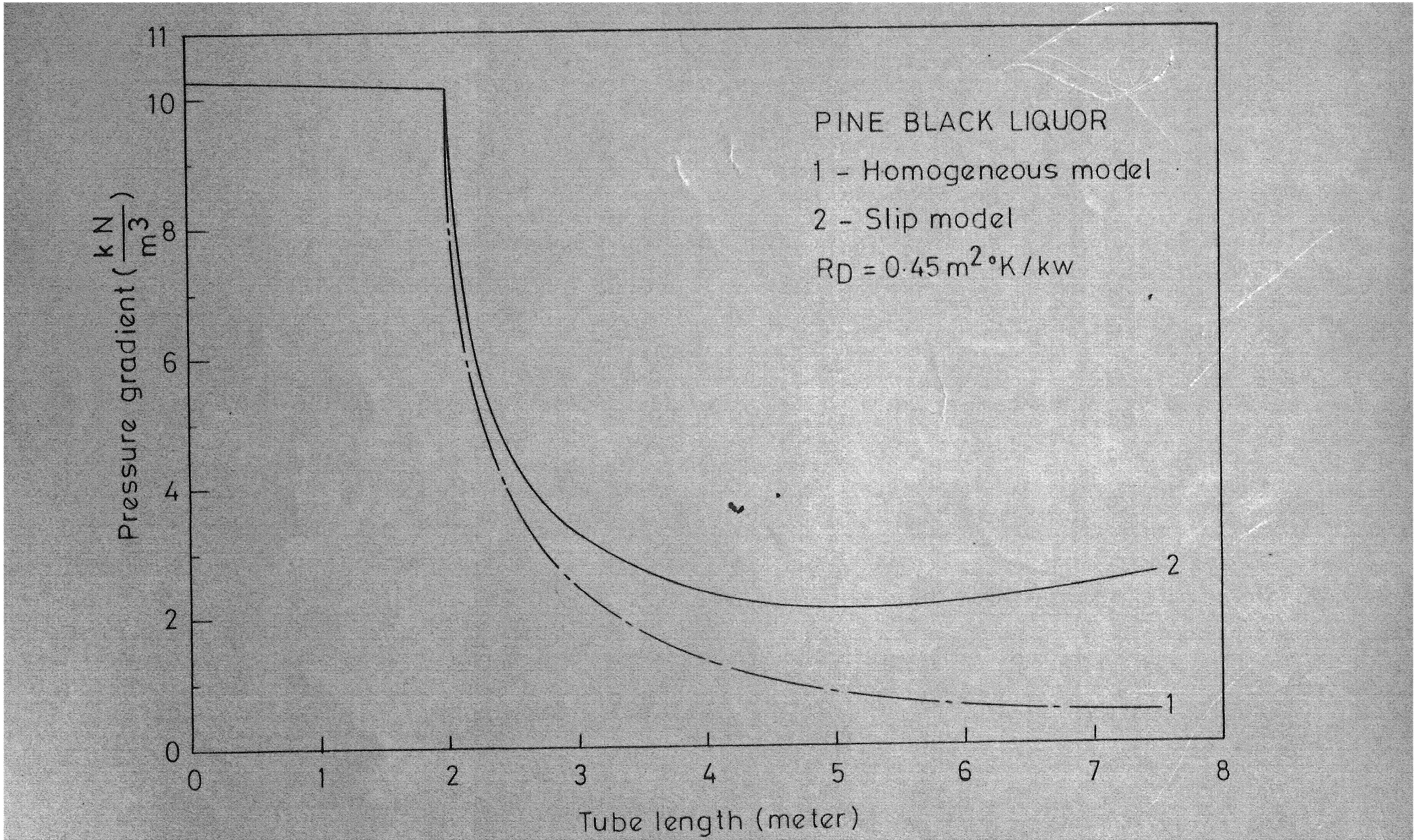


Fig.6.6-Variation of pressure gradient along tube length.

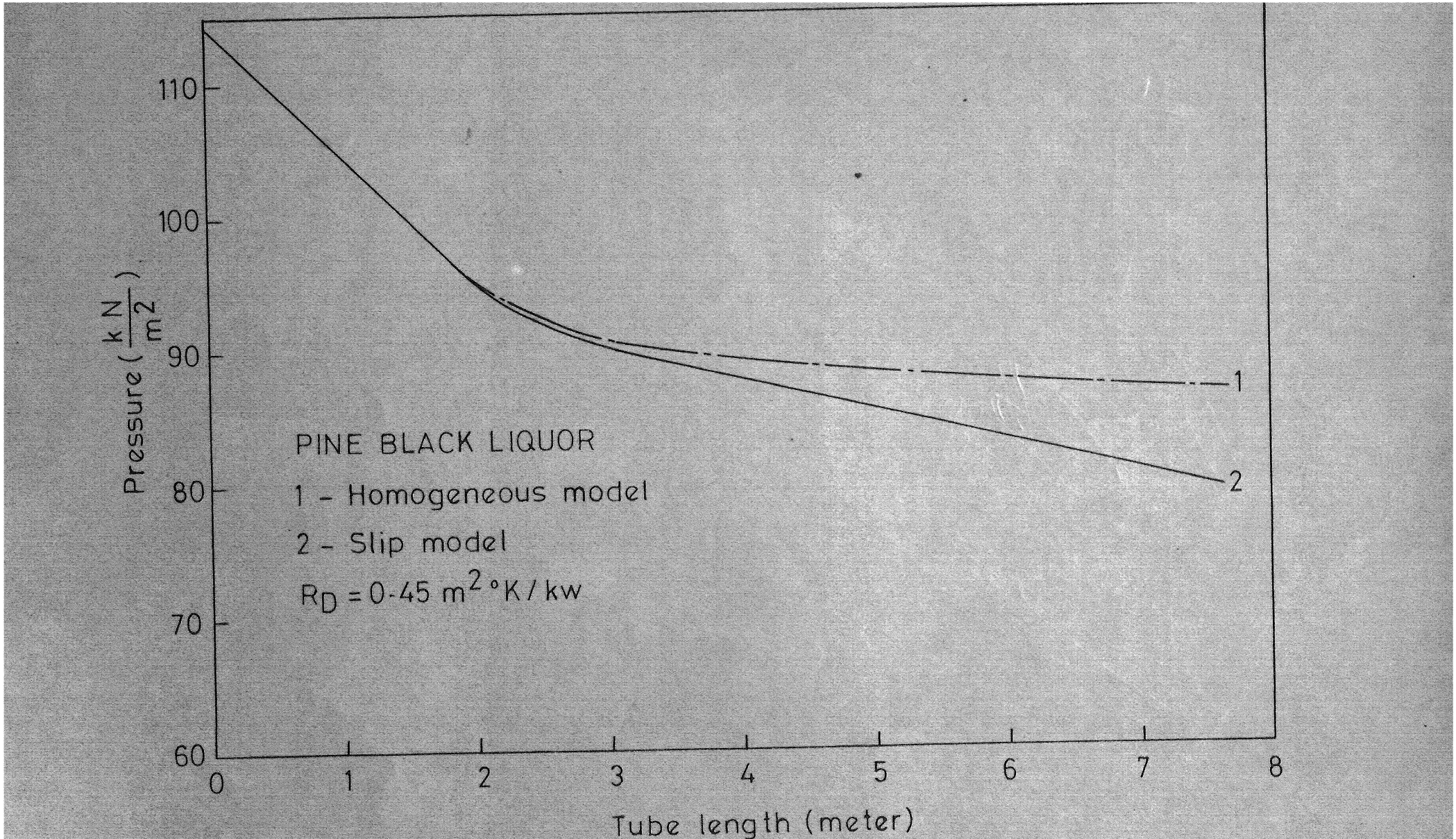


Fig.6.7- Variation of pressure along tube length.

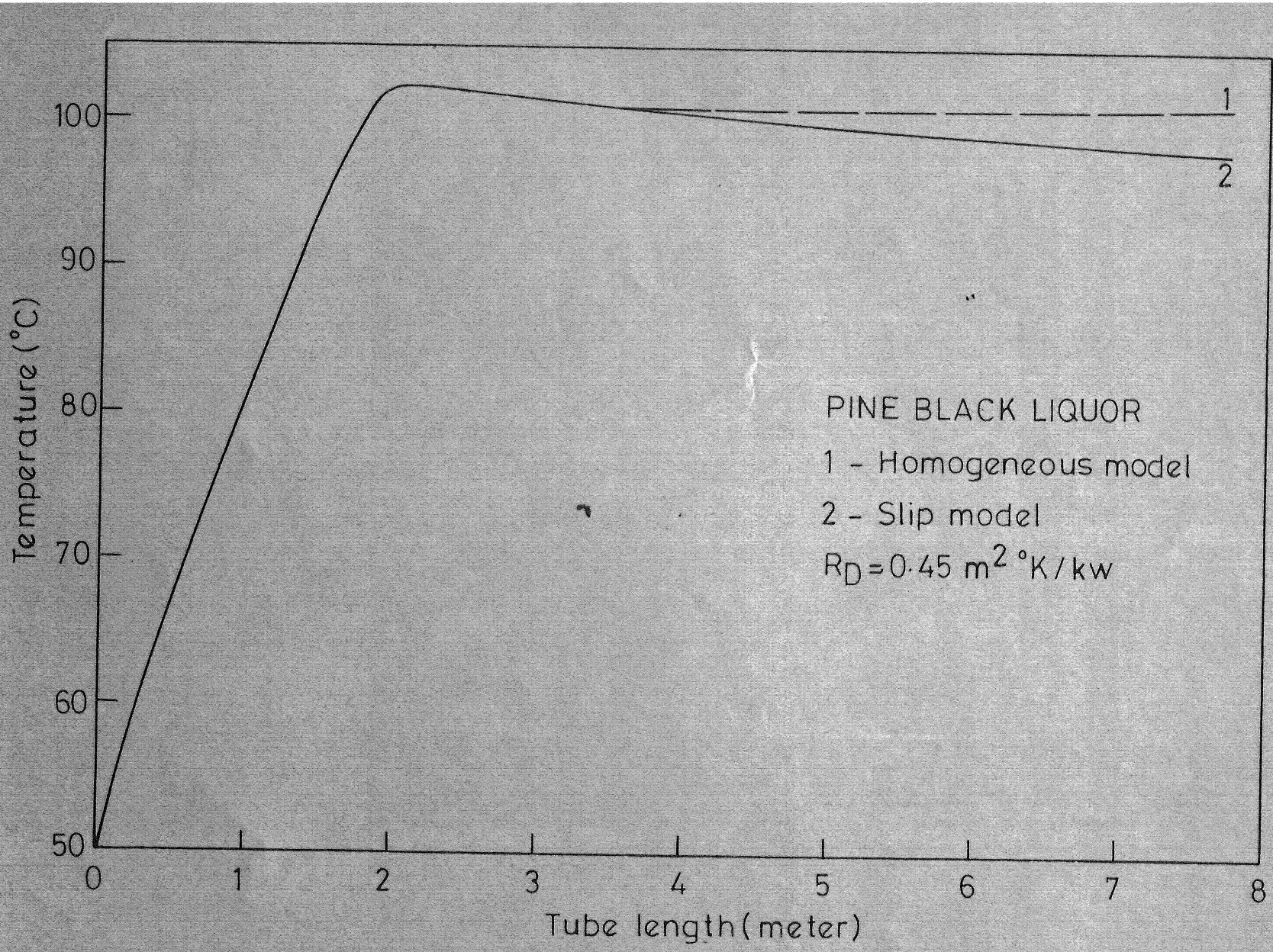


Fig. 6.8 - Variation of liquor temperature along tube length.

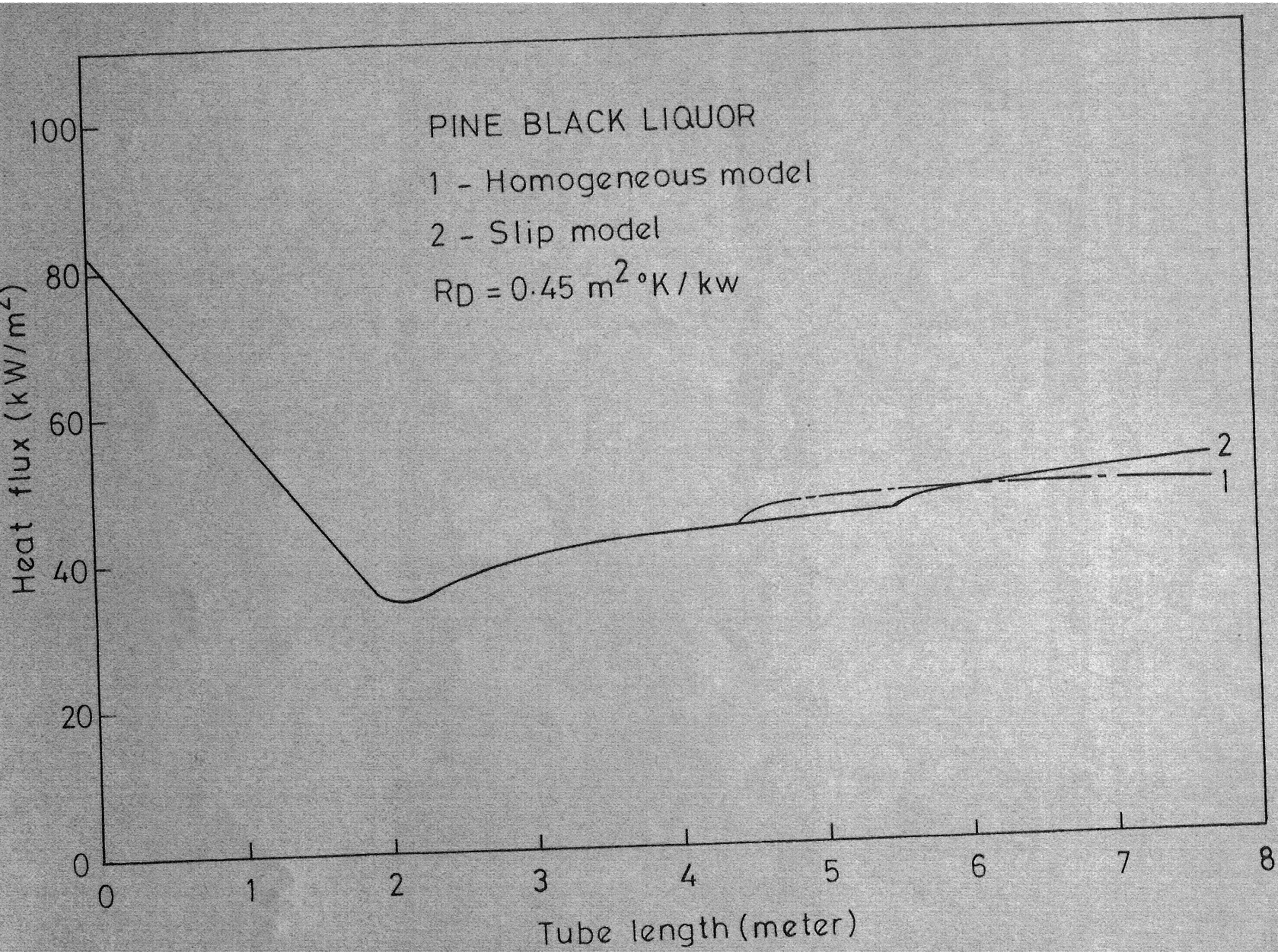


Fig. 6.9 - Variation of heat flux along tube length.

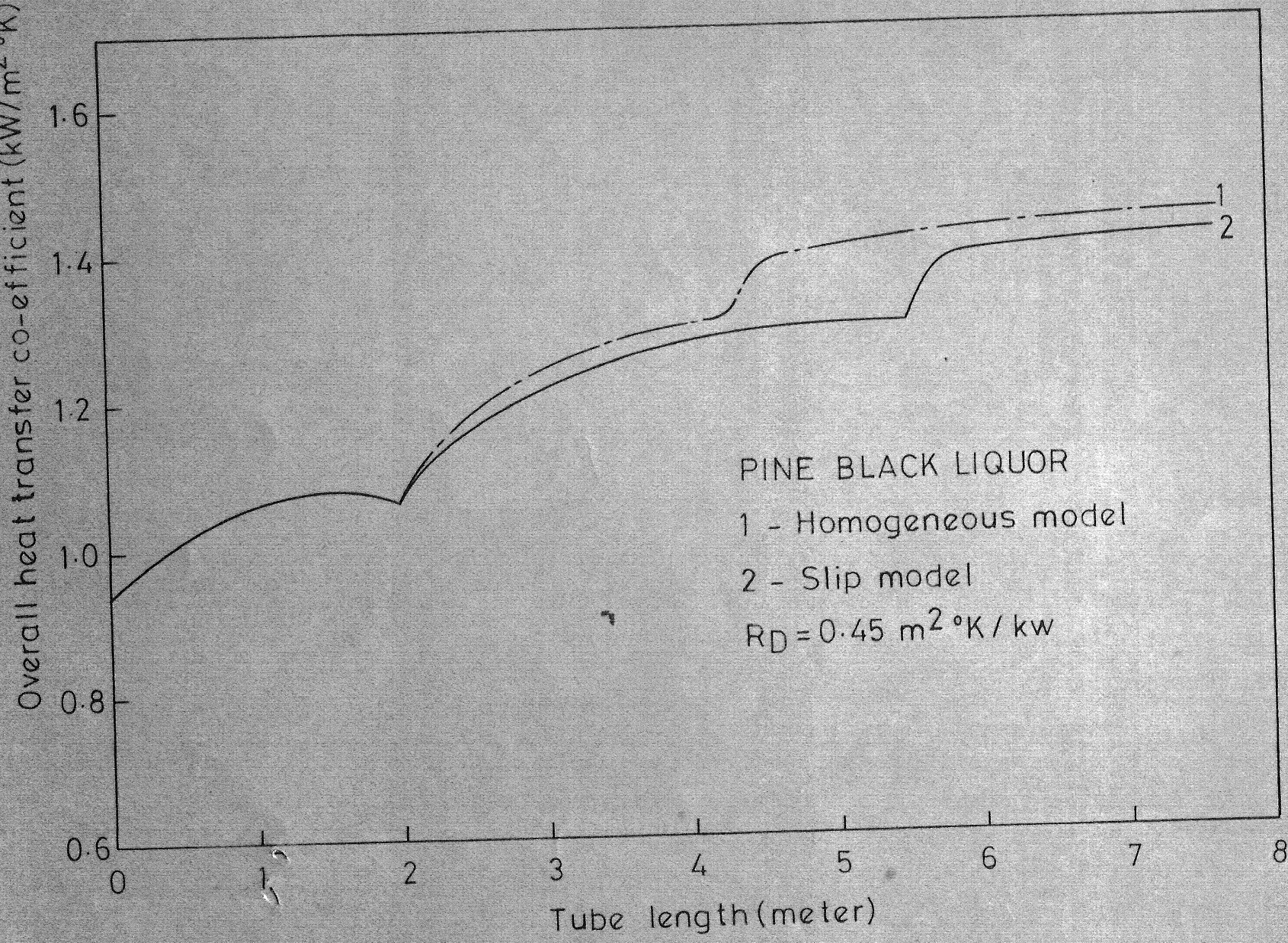


Fig.6.10-Variation of overall heat transfer co-efficient along tube length.

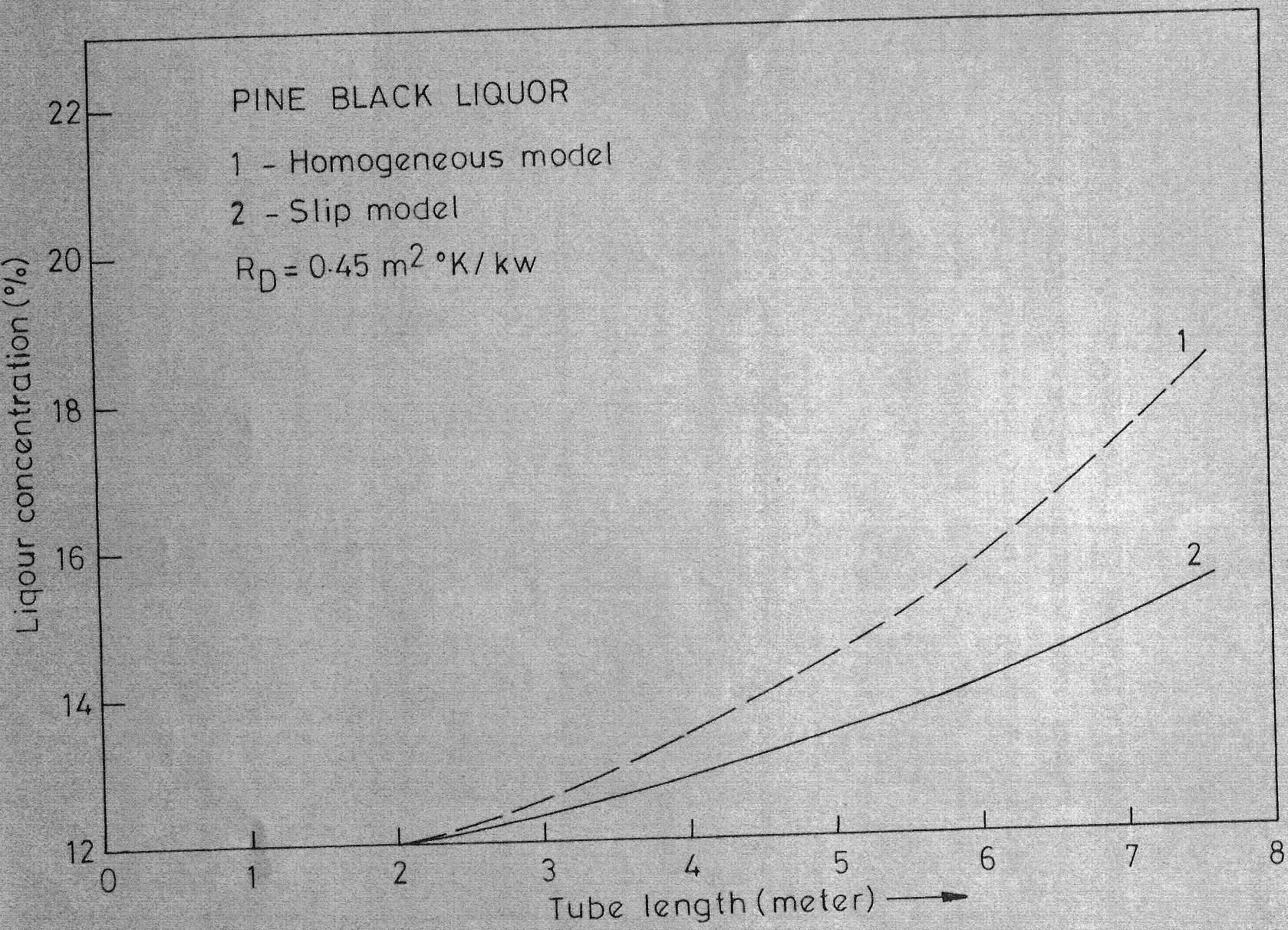


Fig.6.11- Variation of liquor concentration along tube length.

of the evaporator tube is in the range of 0.95 - 0.97.

Change in the pressure gradient along the tube length is given in Fig. 6.6. Pressure gradient decreases slightly in the nonboiling section and subsequently rapidly in the boiling section. The observed decrease in the pressure gradient is due to static and frictional pressure drop effects. The lower value of the pressure gradient for the homogeneous model can be attributed to the fact that in homogeneous model, changes in the momentum of fluid is based on the use of homogeneous phase velocity whereas the slip model takes into account the vapor and liquid velocities during during two phase flow to calculate change in the momentum of fluid. In the upper portion of the tube pressure gradient becomes substantially constant for the homogeneous model whereas it passes through a minima in the slip model which can be attributed to increasing frictional pressure drop in the annular film region. This minima in the pressure gradient corresponds to transition from nucleate boiling to annular film region. The pressure gradient curve for the slip model is similar to experimental results reported by Anderson et.al[15].

Fig. 6.7 shows a gradual decrease in pressure and is caused by static and frictional pressure drop contributions. The steady decline in pressure in the nonboiling section is due to static pressure drop. In the boiling section pressure decreases at a lower rate due to combined effects of hydrostatic head and frictional losses. The curves in Fig.6.7 are similar to experimental curves reported by Anderson et.al.[15].

Fig. 6.8 shows variation of liquor temperature in the tube length. It can be seen that less than one third of the evaporator tube length is used in raising the feed from 50°C to 102.5°C (saturation temperature corresponding to the pressure in the tube) in the nonboiling section. In the boiling section extending over more than two thirds of the evaporator length. The homogeneous model and slip model for the two phase flow predict liquor temperature within 3°C of each other.

Heat flux along the tube length is given in Fig. 6.9 and the values predicted by the homogeneous and slip model are nearly equal. The decrease in the value of heat flux for the nonboiling section is caused by the decrease in temperature driving force as the liquor is being heated to its boiling point. The increasing trend in heat flux over the boiling section in due to the increase in overall heat transfer co-efficient for the nucleate boiling and annular film regions. The transition from nucleate boiling to annular film region occures at 4.3 meter and 5.5 meters from the results of heat flux for the homogeneous and slip models assumptions respectively.

Fig.6.10 gives the variation of overall heat transfer co-efficient along the tube length and shows clearly the three dominant heat transfer mechanisms in a LTV evaporator tube. Out of a total of 7.6 meters long tube the nonboiling, nucleate boiling and annular film regions extend over 2.0,2.3 and 3.3 meters respectively for the homogeneous model and the corresponding lengths for the slip model are 2.0,3.5,2.1 meters. The transition from nonboiling to nucleate boiling and nucleate boiling

to annular film regions are accompanied by a pronounced increase in the value of overall heat transfer co-efficient. In general the homogeneous model predicts higher value for overall heat transfer co-efficient compared to the value based on the slip model. It can be attributed to the higher value of vapor quality for the homogeneous model which results in higher vapor velocity and this leads to higher heat transfer co-efficient than the slip model (eq.4.2,4.3& 4.4).

Fig. 6.11 gives the change in liquor concentration along the tube length and predicts an increase from a initial concentration of 12% to 18.4% and 15.4% at the tube exit end for the homogeneous and slip models respectively. The higher concentrations observed for the homogeneous model is due to the higher value of overall heat transfer co-efficient obtained in Fig.6.10 compared to slip model.

D. Evaporation of Bamboo Black Liquor:

The simulation programme following the flow charts in Fig. 5.1 and 5.3 based on the slip model for two phase flow is used for the evaporation of bamboo black liquor in a single effect LTV evaporator. Physical property correlations reported by Koorse[38] are used in these calculations. Evaporator dimensions and process conditions are chosen to be the same as that used for pinewood black liquor in section C earlier. Two cases of evaporation are assumed for the calculations namely (1) clean tube (2) tube with a dirt resistance of 0.45 m^2 °K/KW. The dependence of the variable on tube length is given in Fig.6.12-6.16 for vapor quality, void fraction, pressure gradient, pressure, temperature, heat flux overall heat transfer co-efficient and solid concentration.

The comparison of the curves 6.12-6.19 with those in Fig.6.4-6.11 shows that the nature of the curves are very similar for the evaporation of Bamboo and pine black liquors. It can be seen from Fig.6.12-6.19 that the contribution of the dirt scale resistance is an important factor and significantly reduces the value of solid concentration obtained for the tubes with clean heat transfer surfaces. Dirt scale resistance increases the tube length corresponding to nonboiling region while decreasing the tube length available for boiling region. For the process conditions assumed for the evaporation of black liquor, the nonboiling section prevailing over 1 meter length of clean tube increases to 2 meter when dirt scale resistance is assumed to 0.45 m^2 °K/KW.

Fig. 6.12 gives variation of vapor quality with tube length and it can be seen that the quality increases from zero at the start of the boiling section to 0.55 and 0.23 towards the end of the tube for clean and fouled surfaces respectively. The higher vapor quality obtainable for the clean surfaces suggest that the process liquor can be evaporated to a higher solid concentration for the given length of the tube. Fouled surface have the effect of decreasing the capacity obtainable using cleaner evaporator tubes.

The graph obtained for the void fraction in Fig.6.13 for bamboo black liquor is essentially identical to the curves obtained for pine black liquor in Fig. 6.5 assuming equal dirt resistance in the tube.

Fig. 6.14 gives the variation of pressure gradient along the evaporator tube. For the last part of the tube length value of pressure

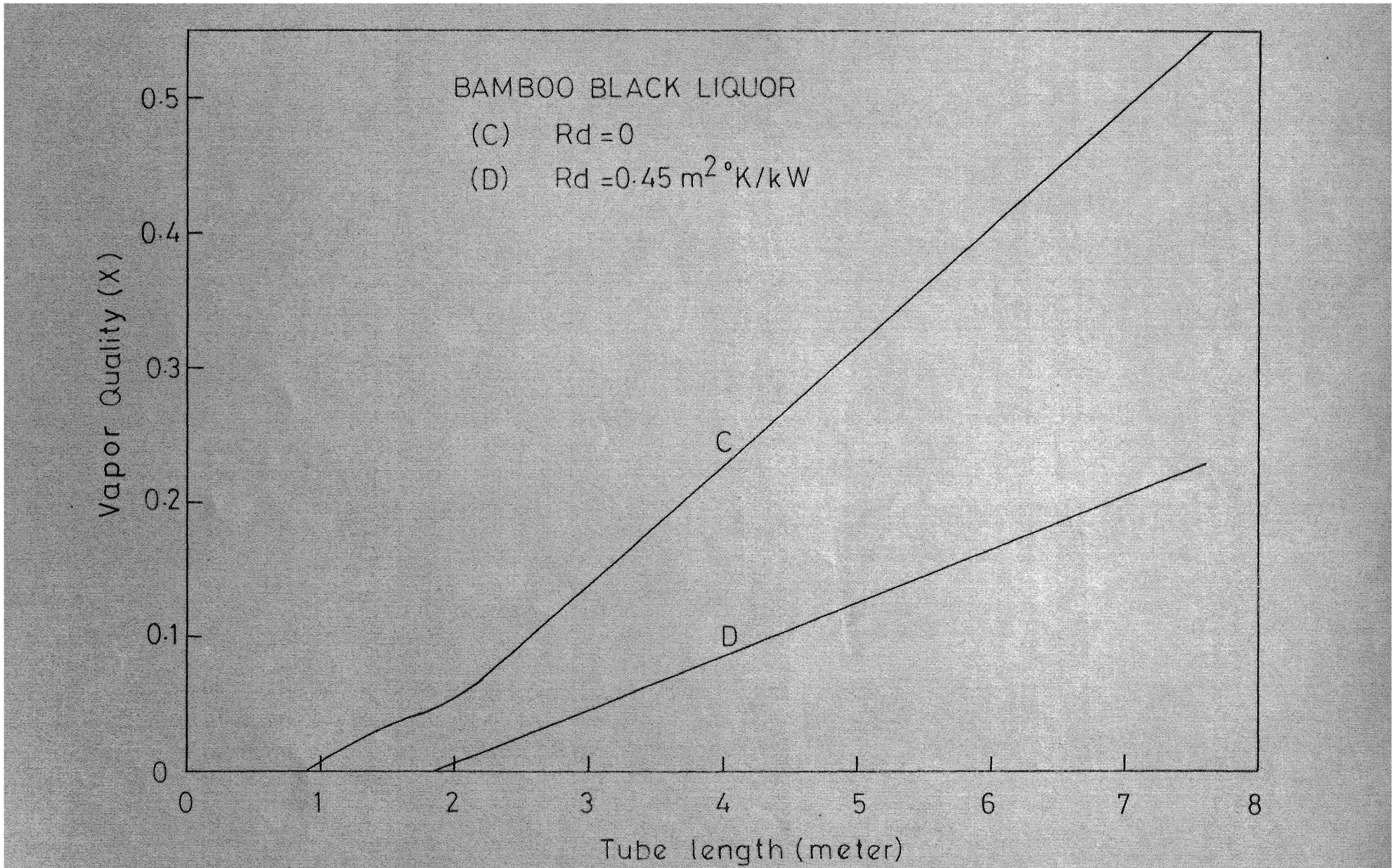


Fig.6.12-Variation of vapor quality along tube length.

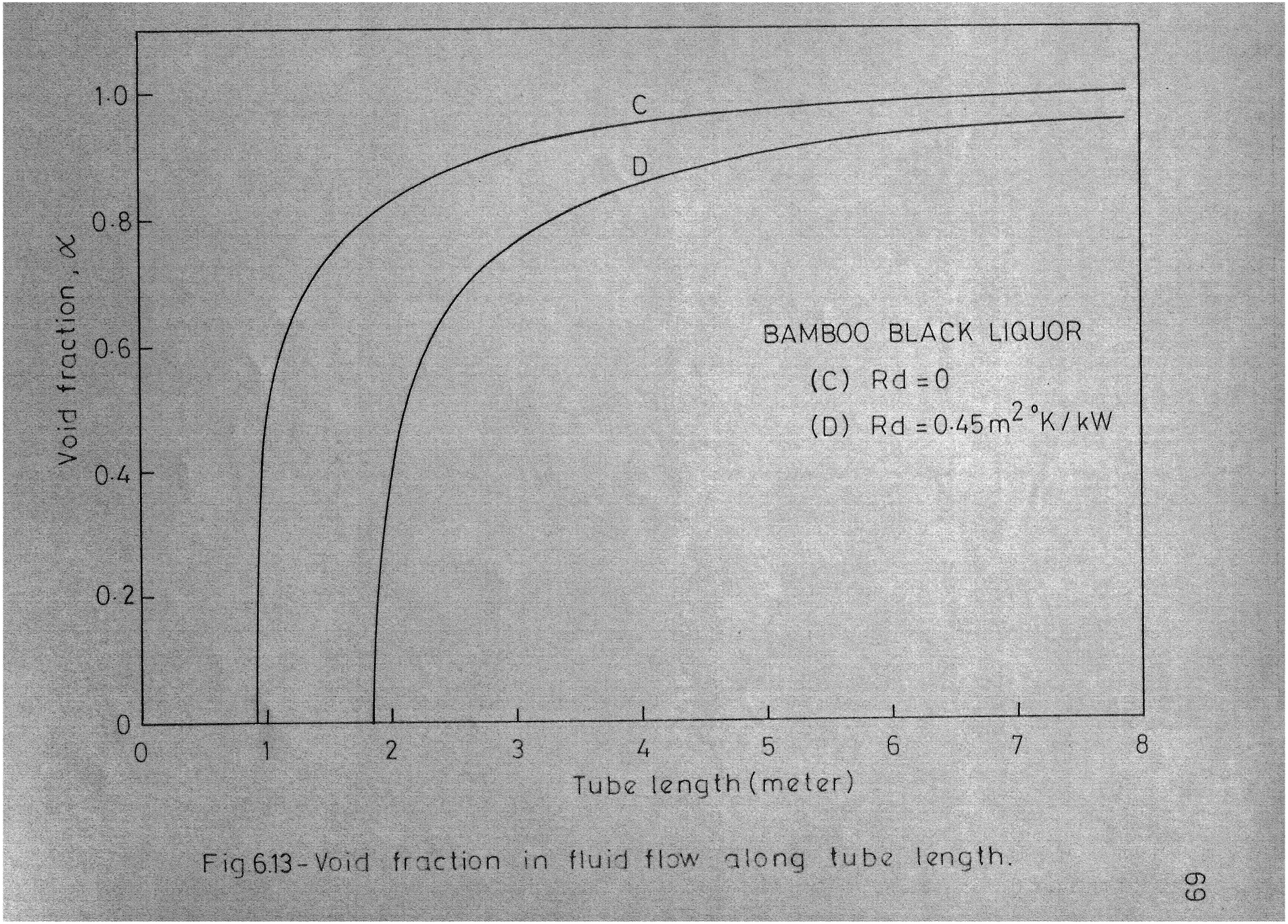


Fig 6.13 - Void fraction in fluid flow along tube length.

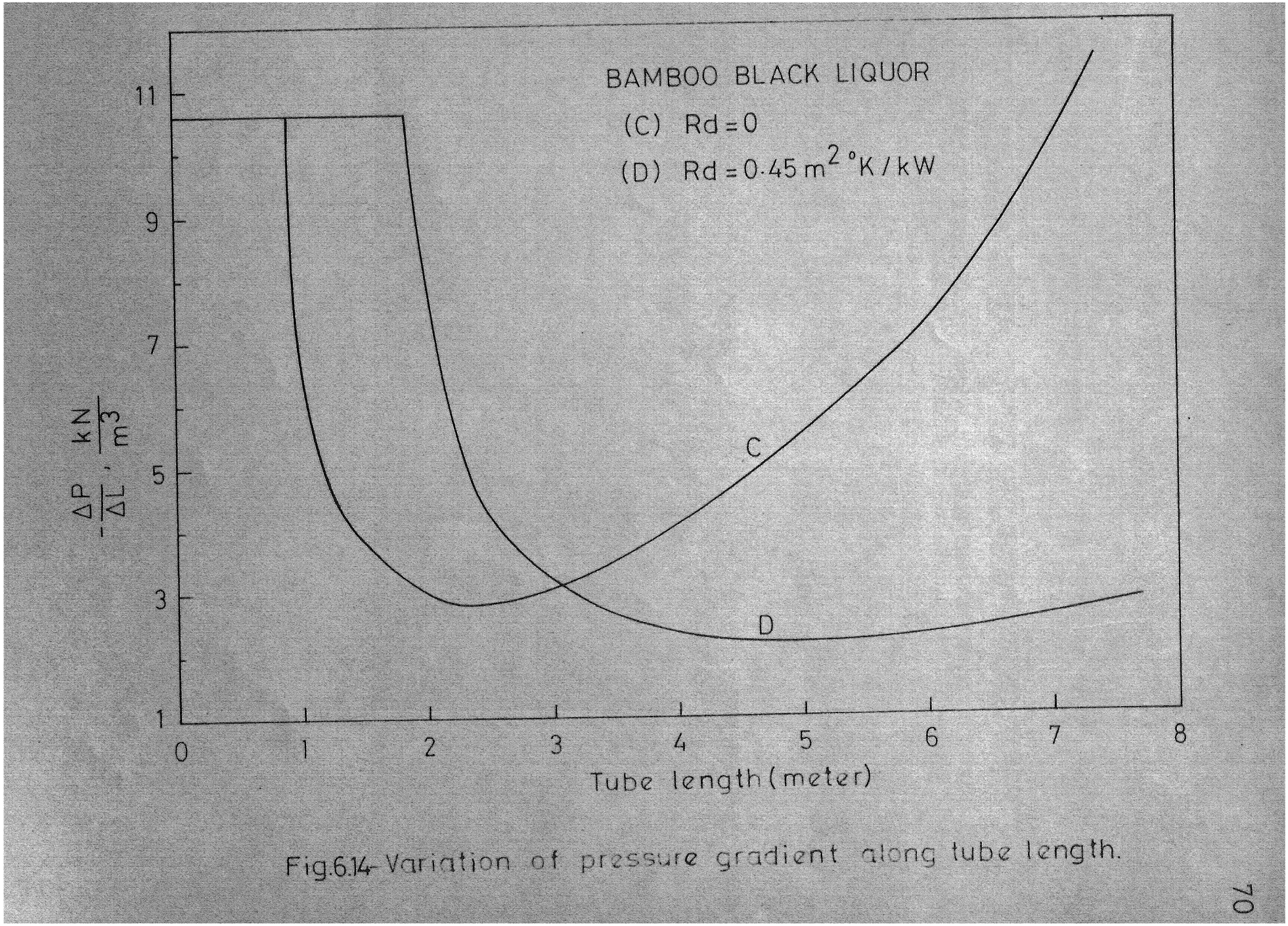


Fig.6.14 Variation of pressure gradient along tube length.

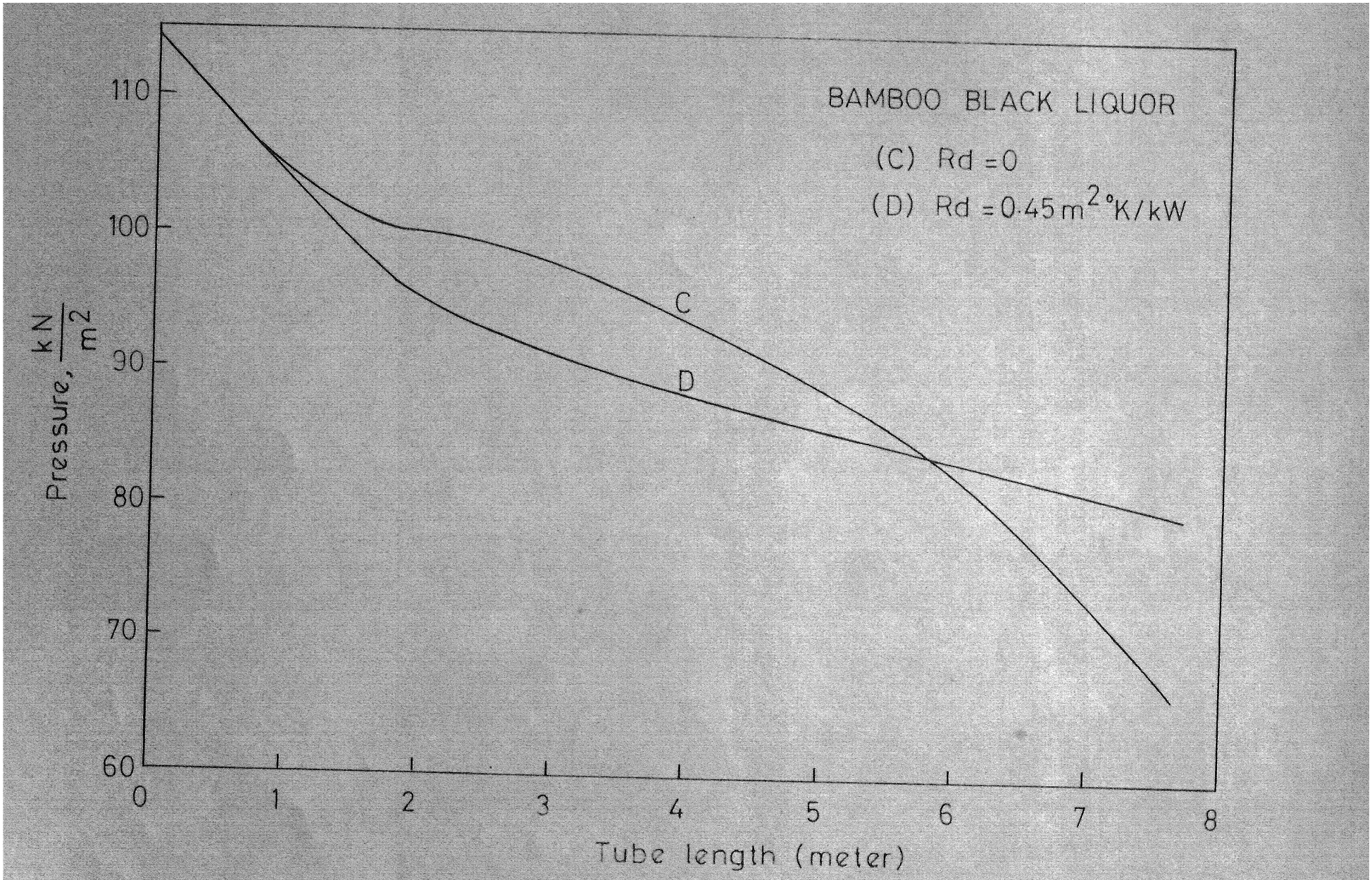


Fig.6.15- Variation of liquor pressure along tube length.

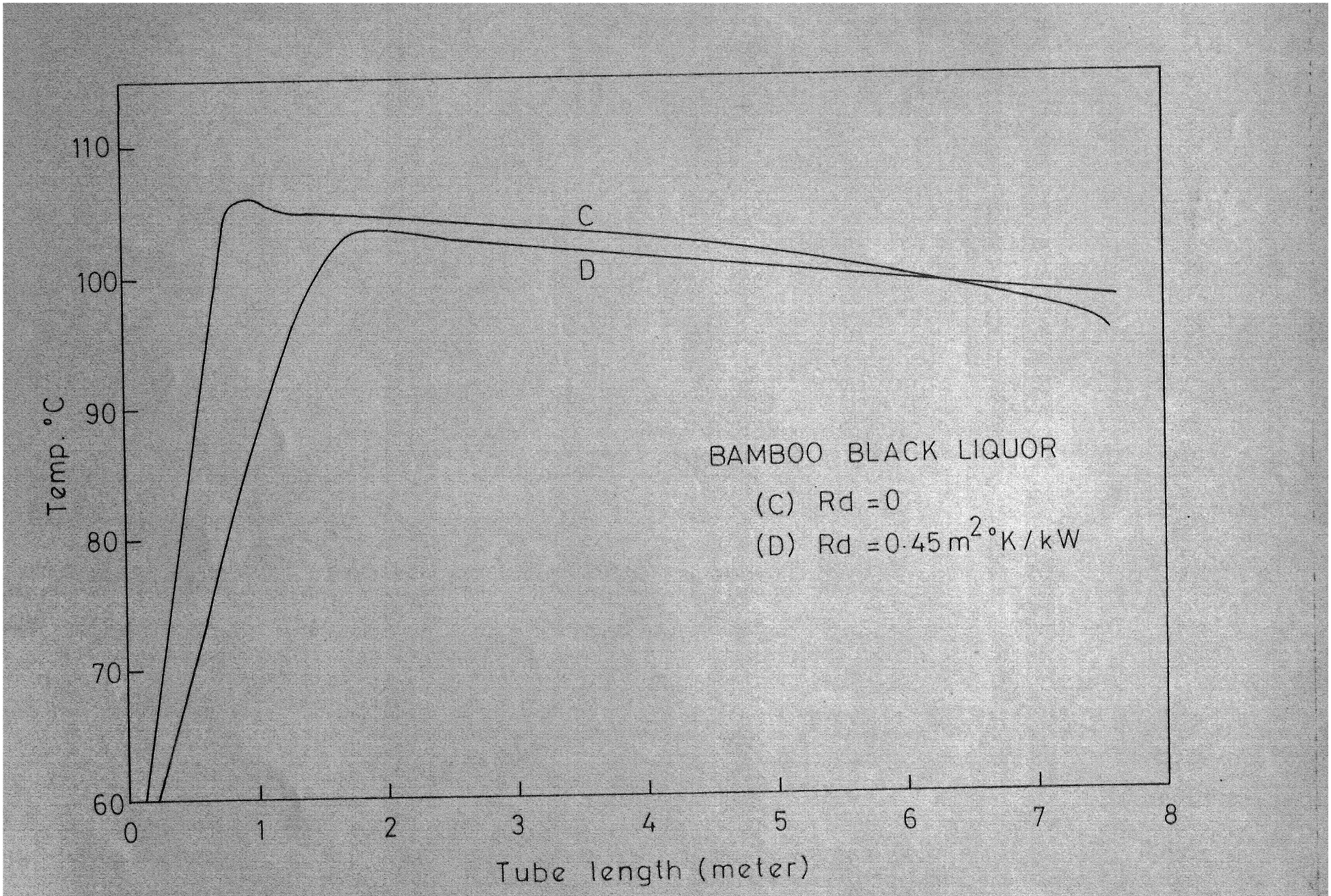


Fig.6.16- Variation of liquor temperature along tube length.

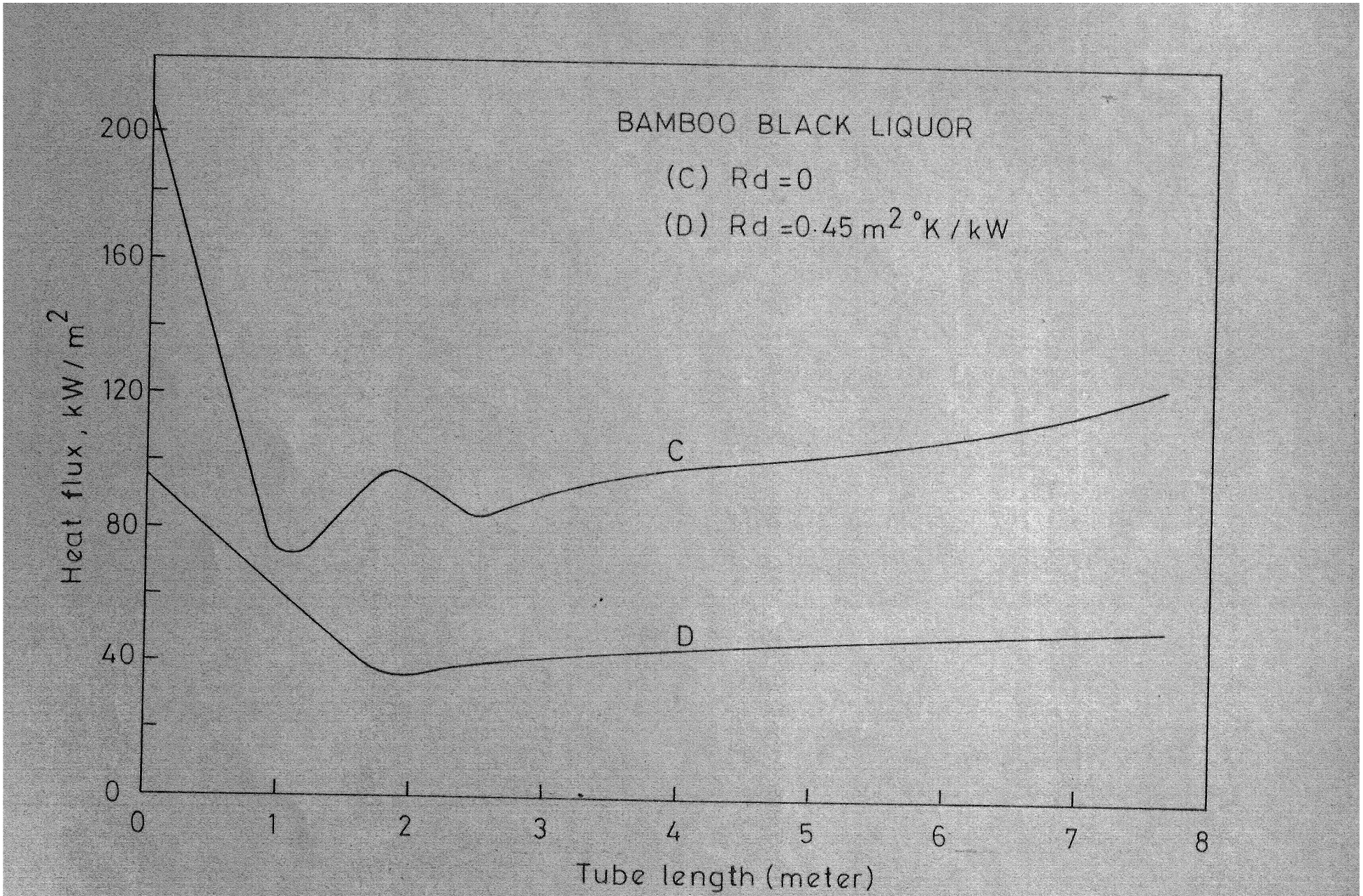


Fig.6.17- Variation of heat flux along tube length.

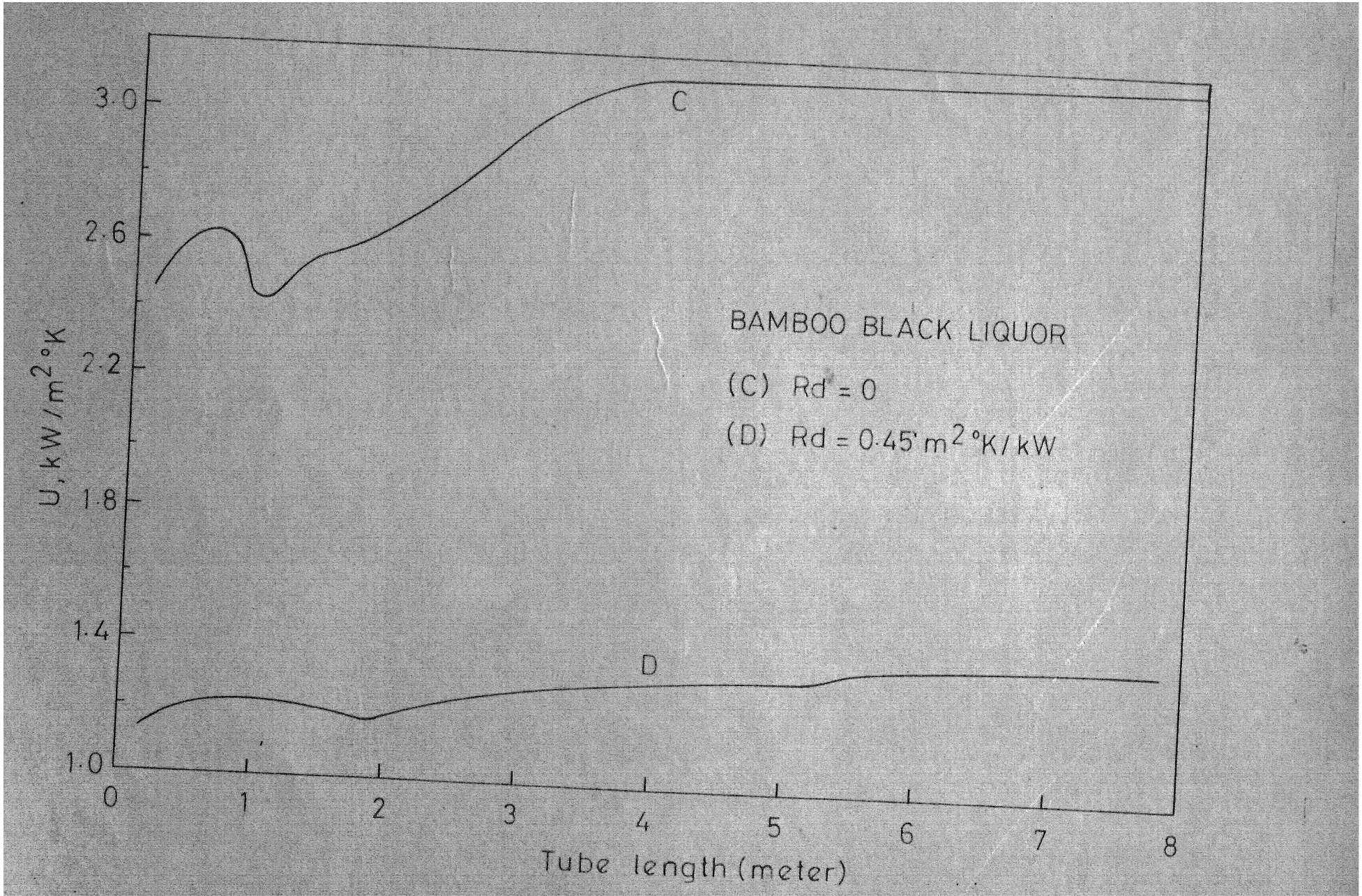


Fig.6.18- Variation of overall heat transfer coefficient along tube length.

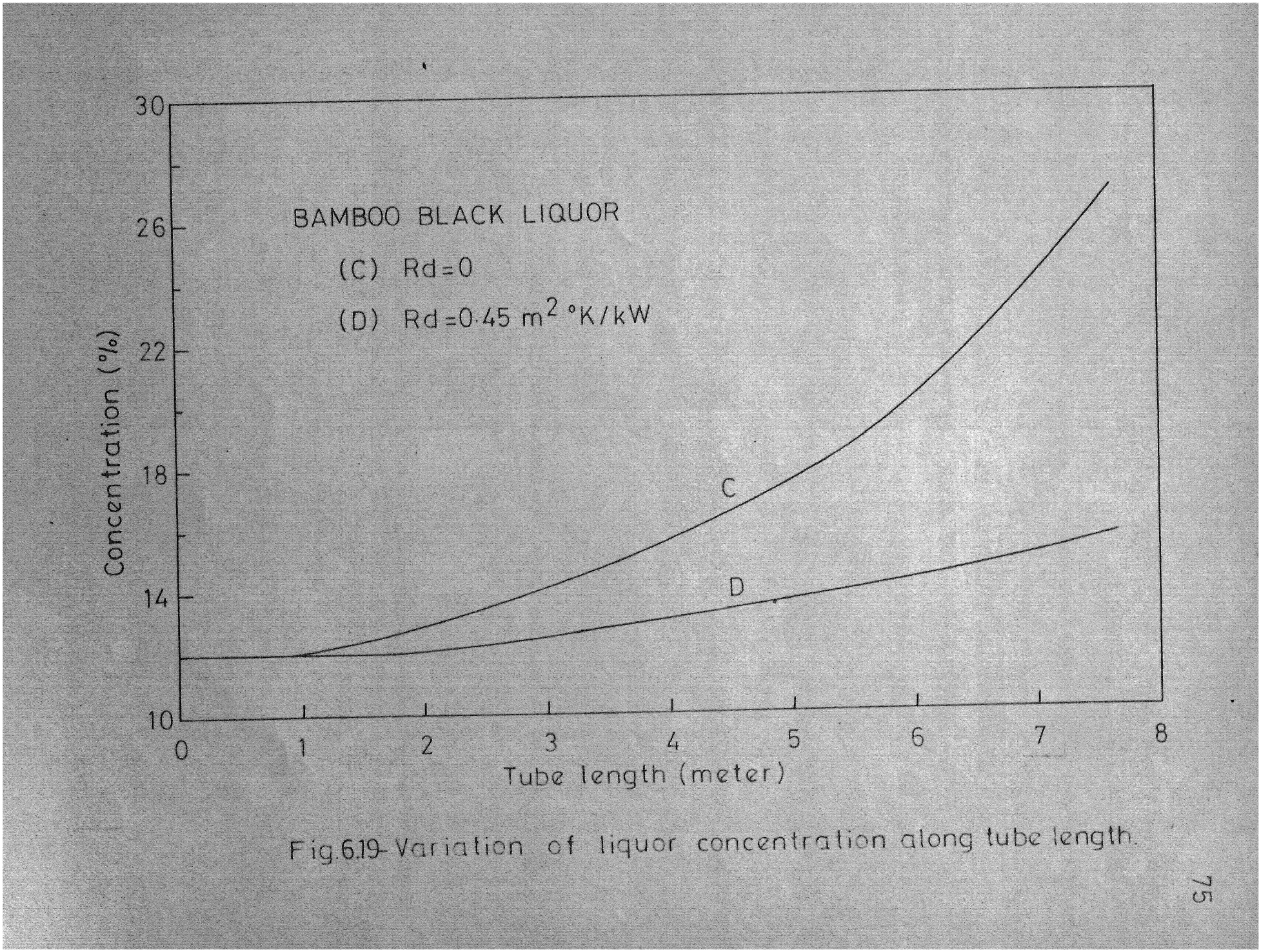


Fig.6.19- Variation of liquor concentration along tube length.

gradient is higher for the clean tube in comparsion to fouled tube. The curves go through a minima at 2.2 and 5.2 meters for the clean and fouled tubes respectively and these lengths represent the transition from nucleate boiling to annular film regions. The pressure gradient in the annular film region is up to 5 times the value for the fouled tubes having the dirt resistance of 0.45 m^2 °K/KW. Such a condition can cause regions of low absolute pressure in the annular film region which may lead to plugging of tubes.

Fig. 6.15 describes the longitudinal variation of pressure along the tube length based on pressure gradient given in Fig. 6.14.

Fig. 6.16 gives the profile of liquor temperature and shows that the maximum value of 106.0 °C for the clean tube and 102.8 °C for the fouled tubes. These profiles are similar to these obtained for pine black liquor in Fig. 6.8.

Fig. 6.17 shows that with clean surfaces it is possible to obtain heat flux rates twice those of the fouled tubes with the assumed dirt resistance value.

The value of the overall heat transfer co-efficient decreases by a factor of 2 to 3 with the assumed value of dirt resistance 0.45 m^2 °K/KW as demonstrated by the graph in Fig. 6.18.

The change in bamboo black liquor concentration in Fig. 6.19 shows that a final concentration of 27.8% and 15.7% can be obtained for the clean and fouled tubes respectively. This points out the need for relatively clean tube surfaces so that satisfactory evaporator capacity

levels can be maintained.

E. Evaporation of Baggase Black Liquor and a Comparison with Bamboo Black Liquor Evaporation:

The computations for the evaporation of baggase black liquors in the single effect LTV unit are identical to the procedure used earlier for pine and bamboo black liquors. The listing of computational procedure for baggase black liquor is given in Appendix D-2 and is based on the same equipment geometry and process feed liquor conditions as used for the other black liquors in this investigation. Fig. 6.20-6.22 gives the profiles of temperature, overall heat transfer co-efficient and solid concentration along the tube length for both clean and fouled tube surfaces. The curves marked C-2 and D-2 denote clean and fouled evaporator tube (R_D =0.45 m^2 °K/KW) respectively for baggase black liquor. For comparison purposes the corresponding results for bamboo black liquor are reproduced in these figures and the curves marked C-1 and D-1 represent clean and dirty tubes (R_D=0.45 m^2 °K/KW) respectively. Baggase and Bamboo black liquors are very good examples for demonstrating the role of engineering properties of process liquors on the performance of evaporators.

The curve in Fig.6.20 show that the temperature profile (C-1) and (D-1) for bamboo black liquor; and (C-2) and (D-2) for baggase black liquor are similar. The length of the nonboiling region is 2.13 meter and 2.75 meter for the clean and fouled tubes respectively handling baggase black liquor and the corresponding value for bamboo black liquor are 0.92 and 1.83 meter. This shows that the nonboiling section length is increased

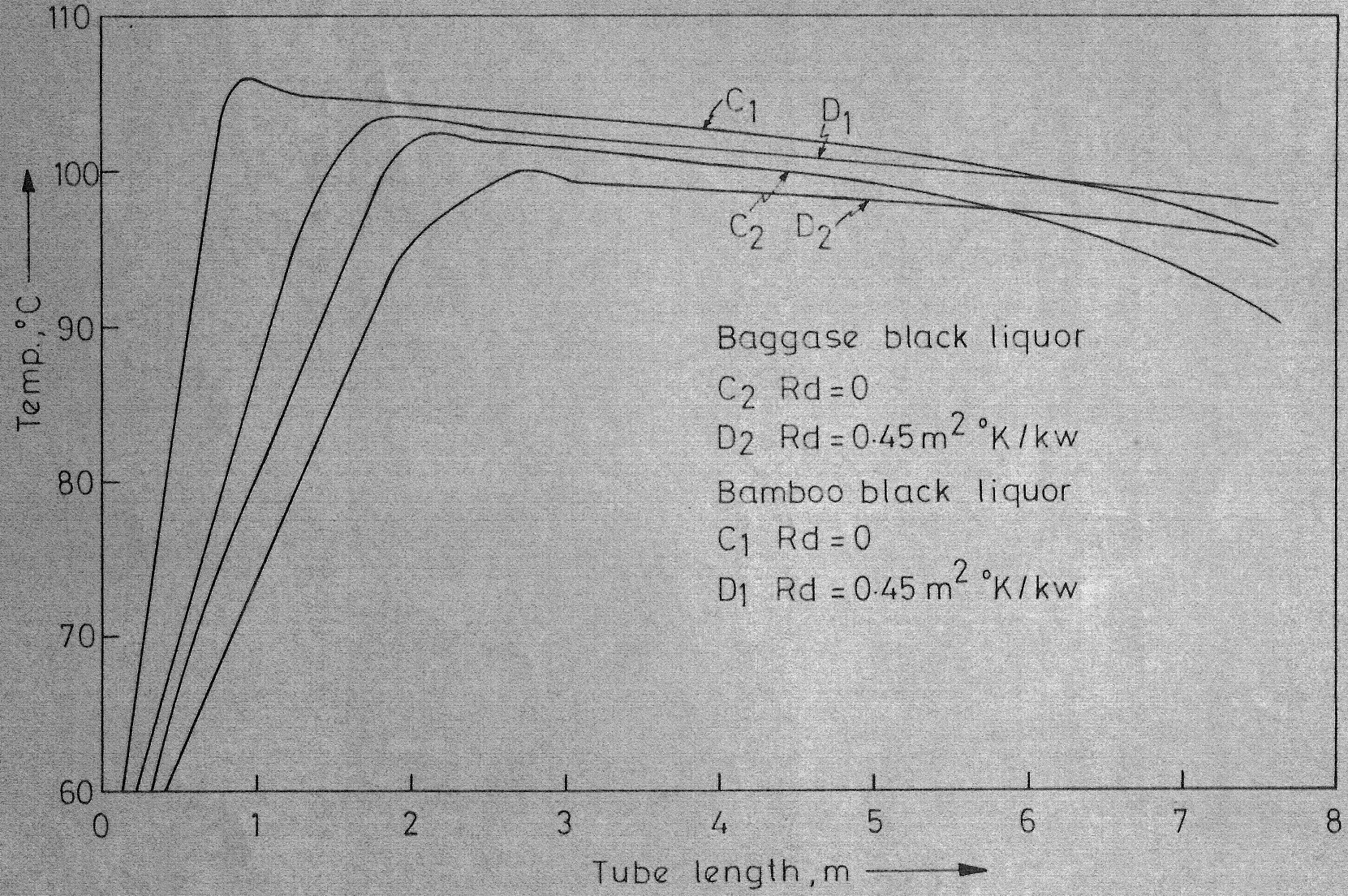


Fig.6.20 Variation of liquor temperature along tube length.

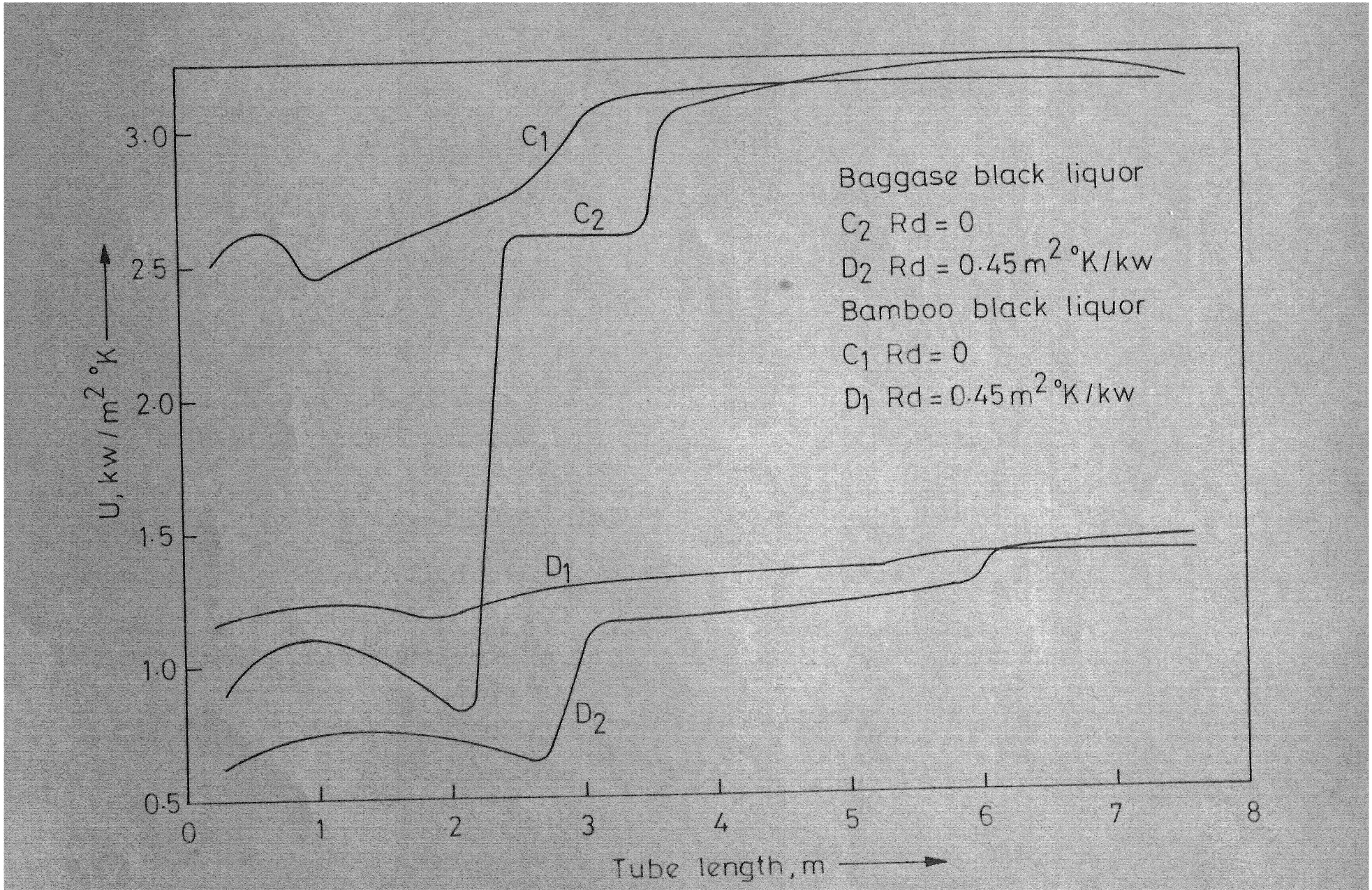


Fig.6.21- Overall heat transfer coefficient along tube length.

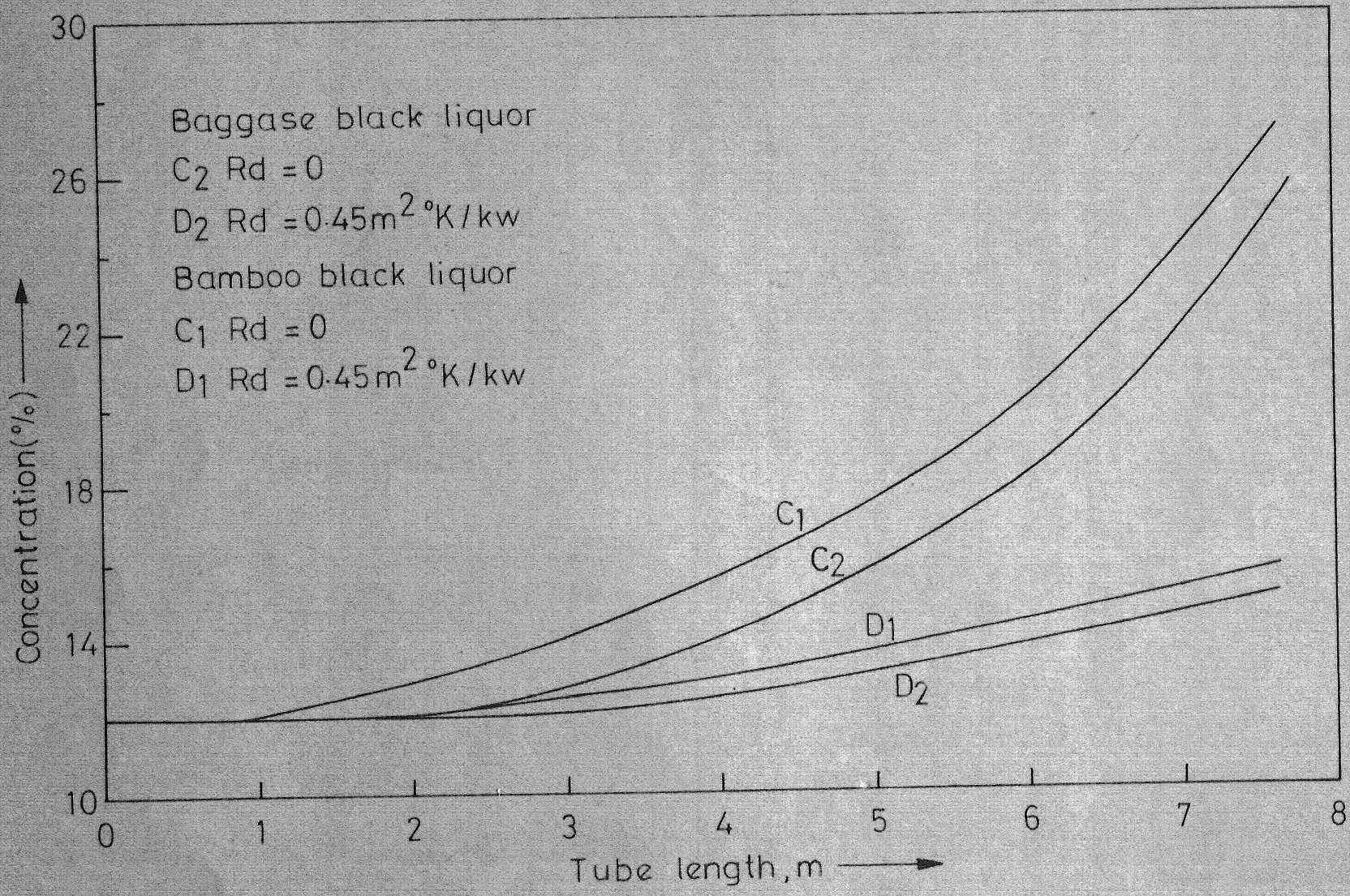


Fig.6.22-Variation of liquor concentration along tube length.

by a factor of 2.3 and 1.5 for clean and fouled surfaces respectively when changing over from bamboo to baggase black liquor. This can be attributed to the lower value of the overall heat transfer co-efficients for baggase black liquor as a result of its higher viscosity.

The curves in Fig. 6.21 show that the value of overall heat transfer co-efficient for bamboo black liquor in the nonboiling section is 2.5 times the value for baggase black liquor. This effect of liquor viscosity on the overall heat transfer co-efficient decreases the evaporation rate as may be observed by the curves in Fig.6.22 (Curves C-1, C-2 and D-1, D-2). The viscosity of the Bamboo and baggase black liquor for the concentration range of Fig.6.22 are given below in Table 6.4.

Table 6.4: Viscosity Range for Bamboo & Baggase Black Liquors in a Clean Tube

	Bamboo Black Liquor		Baggase Black Liquor	
	Inlet	Exit	Inlet	Exit
1. Nonboiling section-				
Temperature, °C	50.0	106.0	50.0	102.4
Solid Concentration, %	12.0	12.0	12.0	12.0
Viscosity, cp	0.9	0.45	4.7	1.9
2. Boiling section-				
Temperature, °C	106.0	95.3	102.4	86.2
Solid Concentration, %	12.0	27.8	12.0	25.9
Viscosity, cp	0.45	1.1	1.9	9.8

The results of the above comparison clearly shows that a given evaporator can be effectively used using preheated baggase black liquor to reduce the length of the nonboiling section. The role of wide variation in physical properties of black liquor can be appreciated in evaluating the performance of commercial plants utilizing multiple effect evaporators including auxilary heat recovery equipments such as liquid preheater, heat exchangers, condensate vaporizers, product vaporizers, vapor bleed etc. Evaporation plant in the chemical recovery system of kraft pulp mill usually consist of 4-7 effects with many of the heat recovery features listed above. The computational scheme for the single effect evaporation developed in this investigation can be applied to multiple effect evaporators which can be suitably modified to incorporate heat recovery features in the simulation programme.

CHAPTER 7

SUMMARY

Simulation programme developed in this work based on slip model for two phase flow can give reliable values of the heat transfer rates in the long tube vertical evaporators. The model has been applied to black liquors over the concentration range of 12-28% dissolved solids and the values of the overall heat transfer co-efficients obtained agree very well with the experimental values reported in literature. The profiles of liquor temperature, concentration, heat flux and overall heat transfer co-efficients along the evaporator tube length are obtained for bamboo, baggase and pine black liquors and the influence of solution viscosity on the lengths of nonboiling, nucleate boiling and annular film regions in a given evaporation unit is illustrated. Reduction in evaporator capacity resulting from the dirt resistance to heat transfer from scale deposits can be predicted by this programme. The model can also be used to predict changes in evaporation capacity and the necessary auxiliary heat exchange equipment when the process liquor exhibits a large change in the viscosity.

NOMENCLATURE

A_L	Cross section of liquid stream, Sq ft.
A_G	Cross section of vapor stream, Sq.ft.
C_1	Cross sectional area of tube, Sq ft
C_L	Specific heat of liquid, Btu/lb °F
C_p	Specific heat of vapor at constant pressure, Btu/lb °F
D	Tube diameter, ft
g	Gravitational Acceleration, ft/sec^2
g_c	Conversion factor, 32.2 $lb\text{-}ft/lb_f . sec^2$
G_G	Mass flux of vapor stream, lb/sq ft. sec.
G_L	Mass flux of liquid stream, lb/sq ft. sec.
G	Mass flux of liquid-vapor stream, lb/sq ft. sec
J	Mechanical equivalent of heat, 778.17 $ft\text{-}lb_f/Btu$
P	Pressure, $lb_f/sq\ ft$
$\frac{dP}{dZ}$	Total pressure drop per unit lengh, $lb_f/cu\ ft.$
$\frac{dP_f}{dZ}$	Frictional pressure drop per unit length, $lb_f/cu\ ft.$
Q	Heat flux, Btu/hr. sq ft.
S	Solid concentration, Wt %
T	Temperature, °F
T_o	Reference temperature, °F
U	Velocity of homogeneous phase
V_G	Velocity of vapor stream, ft /sec

V_L	Velocity of liquid stream, ft/sec.
W_G	Mass flow rate of vapor, lb/sec
W_L	Mass flow rate of liquid, lb/sec
W_T	Total mass flow rate, lb/sec
W_S	Work done by the system on surrounding, Btu/lb-m
X	Quality of vapor-liquor mixture = W_G/W_T
Z	Tube length, ft
ρ_L	Density of liquid, lbm/cu ft.
ρ_G	Denisty of vapor, lbm/ cu ft.
ρ	Density of vapor-liquid mixture, lbm/ cu ft.
τ_W	Shear stress at the wall, lb_f/sq ft.
α	Void fraction
λ	Heat of vaporization, Btu/lbm

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APPENDIX A

TWO PHASE FRICTIONAL PRESSURE DROP

Lockhart & Martinelli[24] have analyzed four types of two phase flow mechanisms which exist during the simultaneous flow of a liquid and a gas or vapor: (1) Turbulent-Turbulent flow (2) Viscous-turbulent flow (3) Turbulent-viscous flow (4) Viscous-Viscous flow (flow of both liquid and gas may be viscous). This analysis is based on the following assumptions:

1. Static pressure drop for the liquid phase must equal the static pressure drop for the gaseous phase regardless of the flow pattern, as long as an appreciable radial static pressure difference does not exist.
2. The volume occupied by the liquid plus the volume occupied by the gas at any instance must equal the total volume of the pipe.
3. Flow mechanism transition criteria:

$Re_{gp} \geq 2000$ the gas phase is turbulent

$Re_{lp} \leq 1000$ flow of liquid is viscous

where $Re_{gp} = \dfrac{4\,W_g}{\pi\, D_p\, \mu_g}$; $Re_{lp} = \dfrac{4\,W_l}{\pi\, D_p\, \mu_l}$

Lockhart & Martinelli defined a parameter X (two phase flow modulus) for the different flow mechanisms given by Eq.A-1 to Eq.A-4.

$$X_{tt}^2 = \left(\frac{W_l}{W_g}\right)^{1.8} \left(\frac{\rho_g}{\rho_l}\right) \left(\frac{\mu_l}{\mu_g}\right)^{0.2} \qquad \text{(A-1)}$$

$$X_{vt}^2 = \frac{C_l}{C_g} Re_{gp}^{-0.8} \frac{W_l}{W_g} \frac{\rho_g}{\rho_l} \frac{\mu_l}{\mu_g} \qquad (A-2)$$

$$X_{tv}^2 = \frac{C_l}{C_g} Re_{lp}^{0.8} \frac{W_l}{W_g} \frac{\rho_g}{\rho_l} \frac{\mu_l}{\mu_g} \qquad (A-3)$$

$$X_{vv}^2 = \frac{W_l}{W_g} \frac{\rho_g}{\rho_l} \frac{\mu_l}{\mu_g} \qquad (A-4)$$

The value of constants C_l, C_g, n, m for use in equation A-1 to A-4 are given below:

Type of Flow	t-t	v-t	t-v	v-v
n	0.2	1.0	0.2	1.0
m	0.2	0.2	1.0	1.0
C_l	0.046	16.0	0.046	16.0
C_g	0.046	0.046	16.0	16.0

The following equations are obtained by least square techniques for the parameter $\phi_g \left[\left(\frac{\Delta P}{\Delta L}\right)_{TP} / \left(\frac{\Delta P}{\Delta L}\right)_g \right]$ and R_g (fraction of tube filled with the vapor) as a function of corresponding X, using curves given by Lockhart & Martinelli for ϕ_g and R_g.

$$\phi_{gtt} = \text{Exp}\ (1.54623+0.48518 \log X_{tt} + 0.044 (\log X_{tt})^2) \qquad (A-5)$$

$$\phi_{gvt} = \text{Exp}\ (1.36397+0.49115 \log X_{vt} + 0.05209 (\log X_{vt})^2) \qquad (A-6)$$

$$\Phi_{gtv} = \text{Exp}\ (1.35883+0.52153 \log X_{tv} + 0.05963\ (\log X_{tv})^2 - 0.0013\ (\log X_{tv})^3 - 0.0004\ (\log X_{tv})^4\ ) \quad \text{(A-7)}$$

$$\Phi_{gvv} = \text{Exp}\ (1.0705+0.5520 \log X_{vv} + 0.0881\ (\log X_{vv})^2 - 0.0026\ (\log X_{vv})^3 - 0.0012\ (\log X_{vv})^4\ ) \quad \text{(A-8)}$$

$$R_g = \text{Exp}\ (-0.2235-0.10046 \log X - 0.0404\ (\log X)^2 - 0.0066\ (\log X)^3) \quad \text{(A-9)}$$

$\Phi_g \left[\left(\frac{\Delta P}{\Delta L} \right)_{TP} \Big/ \left(\frac{\Delta P}{\Delta L} \right)_L \right]$ and R_l (fraction of tube filled with the liquor) can be given by Eq.A-10 and A-11.

$$\Phi_l = \Phi_g / X \quad \text{(A-10)}$$

$$R_l = 1 - R_g \quad \text{(A-11)}$$

Parameter α (flow type modulus for liquid) and β (flow type modulus for vapor) are given by equation A-12 and A-13.

$$\alpha = R_l^4 \Phi_{ltt}^{3.3} = R_l^2 \Phi_{lvt}^2 = R_l^4 \Phi_{ltv}^{3.33} = R_l^2 \Phi_{lvv}^2 \quad \text{(A-12)}$$

$$\beta = R_g^4 \Phi_{gtt}^{3.33} = R_g^4 \Phi_{gvt}^{3.33} = R_g^2 \Phi_{gtv}^2 = R_g^2 \Phi_{gvv}^2 \quad \text{(A-13)}$$

D_l (hydraulic diameter of liquid flow) and D_g (hydralic diameter of gas flow) can be given by Eq. A-14 and A-15.

$$\left(\frac{D_p}{D_l}\right)^2 = \frac{\alpha}{R_l} \qquad \text{(A-14)}$$

$$\left(\frac{D_p}{D_g}\right)^2 = \frac{\beta}{R_g} \qquad \text{(A-15)}$$

Total frictional pressure drop can be calculated by Eq. A-16 by using equations A-1 to A-15.

$$\left(\frac{\Delta P}{\Delta L}\right)_{fric} = \frac{2\left(\frac{4}{\pi}\right)^{2-n} C_l \mu_l^n W_l^{(2-n)}}{D_p^{(5-n)} \rho_l g} \alpha^{(n-2)} \left(\frac{D_p}{D_l}\right)^{(5-n)} \qquad \text{(A-16)}$$

For the case when $R_{egp} > 2100$ and $R_{elp} > 8000$, there is a correction by Davis[25]. For this range Davis defined the parameter X given by Eq.A-17.

$$X = 0.19 \left(\frac{W_l}{W_g}\right)^{0.9} \left(\frac{\rho_g}{\rho_l}\right)^{0.5} \left(\frac{\mu_l}{\mu_g}\right)^{0.1} \left(\frac{Vm^2}{D_p g}\right)^{0.185} \qquad \text{(A-17)}$$

Where $Vm = \left(\frac{W_l}{\rho_l} + \frac{W_g}{\rho_g}\right) \Big/ \frac{\pi D_p^2}{4}$

Notations:

$(\Delta P/\Delta L)_{fric}$ = pressure drop per unit length due to friction, lb-f/cu ft

W_l, W_g = liquid flow rate and gas flow rate respectively, lb/sec.

D_p = Dia of pipe, ft. μ = viscosity, lb-m/sec.ft

ρ = Density lb-m/cu ft.

APPENDIX B

COMPARISON OF TWO METHODS TO CALCULATE NONBOILING SECTION HEAT TRANSFER CO-EFFICIENT

For nonboiling section heat transfer co-efficient, two correlations can be used: equation given by Badger et.al.[6] and equation of Martinelli& Boelter[47]. Badger's correlation gives overall whereas Martinelli & Boelter's expression would give convective heat transfer co-efficient for inside liquid and includes the effect of natural convection

Badger's correlation-

$$U_{NB} = 0.06 \left(\frac{C \Delta T_{NB} \rho^2}{\mu_{NB}} \right)^{0.7} \qquad (B\text{-}1)$$

Martinelli & Boelter's correlation-

$$Nu_{a.m.} = 1.75 \; F1 \left\{ GZ_{a.m} + 0.0722 \; F2 \left(\frac{Gr \; Pr}{X/dw} \right)^{0.84}_{w} \right\} \qquad (B\text{-}2)$$

where

$$F1 = \frac{3.14 \; Nu_{a.m.}/GZ_{a.m.}}{\log (2 + 3.14 \; Nu_{a.m.}/GZ_{a.m.}) \; (2 - 3.14 \; Nu_{a.m.}/GZ_{a.m.})} \qquad (B\text{-}3)$$

$$F2 = 1 - .408 \; \pi \; Nu_{a.m.}/GZ_{a.m.} \qquad \frac{Nu_{a.m.}}{GZ_{a.m.}} < 1.85 \qquad (B\text{-}4)$$

$$= -1.63 \; (\pi \; Nu_{a.m.}/GZ_{a.m.} - 2) \qquad 1.85 < \frac{Nu_{a.m.}}{GZ_{a.m.}} < 2.0 \qquad (B\text{-}5)$$

X = nonboiling section length, ft

Over all heat transfer co-efficient and nonboiling section length are calculated for process conditions of Badger data 7 (see Table 6.1) by

using eq. B-1 and eq. B-2; and are compared below:

Table B-1: Comparison of Results by Badger & Martinelli's Correlations

	Overall Heat Transfer Co-efficient Btu/hr sq ft °F	Nonboiling section length, ft
Badger et.al[6]	90	6.32
Martinelli & Boelter[47]	84	6.53

As clear from Table B-1, both equations lead to nearly same results and for computational purposes it is simpler to use Badger correlation than Martinelli and Boelter expression; in the latter expression nonboiling section length is an implicit variable which will require a trial & error procedure for solution.

APPENDIX C

Table C.1 - Antoine Equation Constants for Water

Temp. Range °C	Antoine Equation Constant		
	A	B	C
0 - 30	8.184254	1791.3	238.1
30 - 40	8.1393986	1767.262	236.29
40 - 50	8.0886767	1739.351	234.10
50 - 60	8.0464204	1715.429	232.14
60 - 70	8.0116295	1695.167	230.41
70 - 80	7.9845588	1678.948	228.97
80 - 90	7.9634288	1665.924	227.77
90 - 100	7.9483960	1656.390	226.86
100 - 150	7.9186968	1636.909	224.92

$$\log_{10} P = A - \frac{B}{T + C}$$

T = temperature, °C

P = pressure, mm of Hg

Table C.2 - Antoine Equation Constants for Water

Pressure Range mm of Hg	Antoini Equation Constants		
	A	B	C
5 - 30	8.184254	1791.3	238.1
30 - 35	8.1393986	1767.262	236.29
35 - 90	8.0886767	1739.351	234.10
90 - 150	8.0464202	1715.429	232.14
150 - 230	8.0116295	1695.167	230.41
230 - 340	7.9845588	1678.948	228.97
340 - 520	7.9634288	1665.924	227.77
520 - 760	7.948396	1656.39	226.86
760 -1500	7.9186968	1636.909	224.92

$$T = \frac{B}{A - \log_{10} P} - C$$

T = temperature, °C

P = pressure, mm of Hg

APPENDIX D

COMPUTER PROGRAMME LISTING

C1	Cross sectional area of the tube
TS	Steam temperature
DP	Internal dia. of tube
XL	Length of the tube
DZ	Differential length increment for computation
WL	Liquor mass flow rate
TI	Inlet temperature of the feed
S	Solid content in the feed
P	Pressure in the tube
WG	Vapor mass flow rate
BPT	Boiling point elevation
GPRLF	Frictional pressure gradient
UN	Overall heat transfer co-efficient
Q	Heat flux
DT	Temperature difference for the differential section
DPT	Pressure drop in the differential section
QT1	Heat transfered in the differential section
QT	Total heat transfered
X	Vapor quality
V	Homogeneous phase velocity
DEG	Density of vapor

XMUG	Viscosity of vapor
HV	Latent heat of vaporization for water
CP	Specific heat of vapor
DX	Vapor quality difference for the section
DS	Solid content change in the differential section
RGI	Void fraction at the inlet of the section
RGO	Void fraction at the outlet of the section
DV	Homogeneous phase velocity difference in the section
HTB	Heat transfered in the boiling section
US2	Average boiling heat transfer co-efficient
DEL	Density of liquor
CL	Specific heat of liquor
UN	Nonboiling section overall heat trasfer co-efficient
XMUL	Viscosity of liquor
WT	Feed liquor mass flow rate
REG	Reynold no for vapor
REL	Reynold no for liquor
RL	Liquid volume fraction in the tube
KL	Thermal conductivity of liquor
ST	Surface tension of liquor
H	Inside tube heat transfer co-efficient for liquor
HS	(Wall + Steam side) Heat transfer co-efficient
U	Overall heat transfer co-efficient in the boiling section

DM	Mean diameter of the tube
DPO	Outside diameter of the tube
SK	Thermal conductivity of tube material
HO	Steam side heat transfer co-efficient
A,B,C	Antoine equation constents

```
£JOB   CGG153,TIME0C8,PAGES040,NAME A.K.AGARWAL
£IBJOB
£IBFTC MAIN
C*************************************************************************&
C*****SINGLE EVAPORATOR USING HOMOGENOUS MCDEL*****
C*****PINEWOOD BLACK LIQUOR IN A TUBE HAVING CIRT RESISTANCE********
C*************************************************************************&
      COMMON C1,TS,DP
      COMMON/LEVEL1/XL
      COMMON/LEVEL2/DZ
       READ 16,XL,DZ,DP
       READ 17,WL,TS,TI,S,P
   16   FORMAT(3F8.4)
   17  FORMAT(5F10.3)
       WG=0.
       PRINT 101
  101  FORMAT(*----------INPUT----------*)
       PRINT 103,WL,TS,TI,S,P
  103  FORMAT(* WL= *,F10.3,* LB-M/SECOND*,/* TS= *,F10.3,* DEGREE F *,/*
     / T=*,F10.2,* DEGREE F *,/* SOLID CONTENT= *,F10.3,* PERCENT *,/* P
     /= *,F10.3,* LBF/SQ FT *)
       PRINT 102
  102  FORMAT(*----------OUTPUT----------*)
       NE=1
        C1=(3.14*DP**2.)/4.
        T=TI
       PRINT 1
    1   FORMAT(*----------EVAPORATOR NO 1----------*)
        CALL EVAP(WL,WG,S,T,P,NE)
         STOP
        END
£IBFTC EVAP
       SUBROUTINE EVAP(WL,WG,S,T,P,NE)
C*************************************************************************&
C*****SINGLE EVAPORATOR CACULATIONS*****
C*************************************************************************&
       COMMON C1,TS,DP
       COMMON/LEVEL1/XL
       COMMON/LEVEL2/DZ
          XN=XL/DZ
        DT=0.0
        QT=0.0
       N=0
       CALL VPT(P,BPT)
C    ****CHANGE CARD FOR BOILING POINT ELEVATION****
       BPT=BPT+.19*S*9./5.
       IF(T-BPT)37,35,35
   37  IF(NE.EQ.2) GO TO 35
       IF(NE.EQ.3) GO TO 35
    1   DZ1=DZ
        CALL EML(WL,T,S,GPRLF,U,Q,UN,DT,DT1,DPT,DZ1,TX,P)
       QT1=Q*3.14*DP*DZ1
         QT=QT+QT1
         PRINT 9
        P=P+DPT
```

```
      DPF=-GPRLF*DZ1
       PRINT 8,P,DPT,DPF
    8  FORMAT(* PRESSURE= *,F16.8,* LB/SQ FT *,//* TOTAL PRESSURE DROP=
     /*,F16.8,* LB/SQ FT *,//* FRICTIONAL PRESSURE DROP= *,F16.8,* LB/SQ
     / FT *)
    9  FORMAT(110(1H-))
       PRINT 10,WL,S,T,U,UN,Q,QT1,QT
   10   FORMAT(* MASS FLOW RATE OF BLACK LIQUOR= *,F16.4,* LB M PER SECO
     /ND *,//* SOLID CONTENT= *,F16.4,* PERCENT *,//* TEMPERATURE= *,F16
     /.4,* DEGREE FAHRENHEIT *,//* FLOW-VELOCITY= *,F16.4,* FT PER SECON
     /D *,//* OVER-ALL HEAT TRANSFER CO-EFFICIENT= *,F16.4,* BTU/HR.SQ F
     /T.DEG F *,//* HEAT FLUX= *,F16.4,* BTU/HR.SQ FT *,//* HEAT TRANSFE
     /RRED IN THE SECTION= *,F16.4,* BTU/HR *,//* TOTAL HEAT TRANSFERRED
     / UP TO THIS SECTION= *,F16.4,* BTU/HR *)
       N=N+1
       PRINT 14,TX
   14   FORMAT( *BOILING POINT AT THIS PRESSURE= *,F16.4,* DEGREE  F *)
       XL=XL-DZ1
       PRINT 18,XL,DZ1
   18  FORMAT(* REMAINING HEIGHT= *,F16.2,* LENGTH INCREMENT= *,F16.3)
        PRINT 13,N
    13 FORMAT(* COMPUTATION FOR SECTION *,I3,* HAS BEEN COMPLETED *)
        PRINT 9
       IF(T-TX)2,3,3
    2  CONTINUE
       PRINT 11
   11  FORMAT(* CALCULATION FOR NEXT LENGTH INCREMENT--- *)
        DT=0.0
       GO TO 1
    3   PRINT 15
   15   FORMAT(* CALCULATION FOR NONBOILING SECTION IS COMPLETE *)
   35  PRINT 36
   36  FORMAT(* THERE IS NO NONBOILING SECTION *)
C      BOILING SECTION NO-1
       XN=XL/DZ
       N=0
       WT=WL+WG
       X=WG/WT
       V=WT/(C1*62.43)
       TR=2.0
       DP1=-40.0
       DT=0.
       CALL PP(T,DT,DEG,DEG1,XMUG,HV,CP)
       DX=225.*3.14*DP*DZ*(TS-T)/(3600.*WT*HV)
   25  DV=0.
   31  DT=0.
       DS=0.
       CALL EMC(WT,X,S,T,P,V,DX,DS,DT,DPP,DV,TR,Q,WL,WG,U,RGI,RGO)
       T=T+DT
       X=X+DX
       V=V+DV
       P=P+DPP
       S=S+DS
       QT1=Q*3.14*DP*DZ
       QT=QT+QT1
```

```
      PRINT 9
      PRINT 28,RGI
   28 FORMAT(* VOID FRACTION AT INLET= *,F16.3)
      PRINT 26,WL,WG,X,T,V,P,S,U,Q,QT1,QT,DPP
   26 FORMAT(* WL= *,F16.4,* LB-M/SECOND *,/* WG= *,F16.4,* LBM/SECOND*,
     //* X= *,F16.4,/* T= *,F16.4,* DEGREE F *,/* V= *,F16.4,* FT/SECOND
     / *,/* PRESSURE= *,F16.4,* LBF/SQ.FT *,/* SOLID CONTENT= *,F16.4,*
     / PERCENT *,/* OVER ALL HEAT TRANSFER CO-EFFICIENT= *,F16.4,* BTU/H
     /R.SQFT.DEGREE F *,/* HEAT FLUX= *,F16.4,* BTU/HR.SQFT *,/* HEAT TR
     /ANSFERRED IN THE SECTION= *,F16.4,* BTU/HR *,/* TOTAL HEAT TRANSFE
     /RRED= *,F16.4,* ETU/HR *,/* PRESSURE DROP= *,F16.4,*  LBF/SQFT *)
      PRINT 29,RGO
   29 FORMAT(* VOID FRATION AT OUTLET= *,F16.3)
      PRINT 9
      N=N+1
      PRINT 13,N
      IF(FLOAT(N)-XN)21,24,24
   21 IF((XN-FLOAT(N))-1.)32,33,33
   32 DZ=(XN-FLOAT(N))*DZ
   33 IF(RGO-0.9) 34,30,30
   34 IF(DPP-DP1) 22,23,23
   22 IF(RGO-.8)23,30,30
   30  TR=3.
      PRINT 27
   27 FORMAT(* REGION IS ANNULAR *)
   23 DP1=DPP
      GO TO 25
   24 CONTINUE
      RETURN
      END
£IBFTC EML
      SUBROUTINE EML(WL,T,S,GPRLF,U,Q,UN,DT,DT1,DPT,DZ,TX,P)
C*************************************************************&
C*****ENERGY,MOMENTUM AND CONTINUITY EQUATIONS FOR SINGLE PHASE LIQUID***
C*************************************************************&
      COMMON C1,TS,DP
    5 CALL PRLT(WL,T,S,GPRLF,DPF,DZ)
      CALL XDEL(S,T,DEL)
      CALL XCL(S,T,CL)
      U=WL/(DEL*C1)
      DPT=-DEL*DZ-1.0*GPRLF*DZ
      DELT=TS-T
      CALL XUN(TS,T,S,UN)
      Q=UN*DELT
      R=DP/2.0
      A=Q*2.0*3.14*R*DZ/(CL*3600.0*DEL*U*C1)
      B=DZ/(7.7817*100.0*CL)
      DT1=A-B
      IF(ABS(DT-DT1)-0.1)1,1,2
    2 T=T+(DT1-DT)/2.0
      DT=DT1
      GO TO 5
    1  T=T+(DT1+DT)/4.0
      P=P+DPT
      P=P*760.0/(144.0*14.7)
```

```
      TX=(1656.390/(7.9484-ALOG10(P)))-224.92
      P=P*144.0*14.7/760.0
      P=P-DPT
      TX=9.0*TX/5.0+32.0
       TX=TX+4.0
      IF(TX-T)7,6,6
    7 IF((T-TX)-.5)6,6,8
    8 DZ=DZ*.8
      T=T-(DT1+DT)/2.
      DT=0.
      GO TO 5
    6 CONTINUE
      RETURN
       END
£IBFTC PRLT
      SUBROUTINE PRLT(WL,T,S,GPRLF,DPF,DZ)
C*************************************************************&
C*****CACULATES NONBOILING SECTION LIQUID FRICTIONAL PRESSURE DROP****
C*************************************************************&
      COMMON C1,TS,DP
       CALL MUL(S,T,XMLL)
       CALL XDEL(S,T,DEL)
       CALL MUL(S,TS,WMUL)
       V=WL/(DEL*C1)
      RE=DEL*V*DP/XMUL
       IF(RE-2100.0)1,1,2
    1  F=16.0/RE
       F=F*(WMUL/XMUL)**0.38
      GO TO 3
    2  A=4.0*ALOG10(2./0.00015)
      F=(1.0/(A+2.28))**2.0
      F=F*(WMUL/XMUL)**0.17
    3  DPF=-2.0*F*DZ*V**(2.0)*DEL/(DP*32.2)
       GPRLF=-DPF/DZ
      RETURN
       END
£IBFTC XUN
      SUBROUTINE XUN(TS,T,S,UN)
C*************************************************************&
C    ****NONBOILING SECTION OVERALL HEAT TRANSFER COEFFICIENT****
C*************************************************************&
       CALL XCL(S,T,CL)
       CALL MUL(S,T,XMLL)
       CALL XDEL(S,T,DEL)
       XMUL=3600.0*XMUL
      DELT=TS-T
       UN=0.06*(CL*DELT*DEL**2.0/XMUL)**0.7
      A=1./UN+.0025
      UN=1./A
       RETURN
       END
£IBFTC EMC
C*************************************************************&
C*****HOMOGENOUS MODEL FOR ENERGY,MOMENTUM AND CONTINUITY EQUATIONS*****
C*************************************************************&
```

```
      SUBROUTINE EMC(WT,X,S,T,P,V,DX,DS,DT,DPP,DV,TR,Q,WL,WG,U,RGI,RGO)
      COMMON C1,TS,DP
      COMMON/LEVEL2/DZ
   10 CALL PRF(WT,X,T,S,DX,DT,DS,GPRF,RG,P)
      CALL XDEL(S,T,DEL)
      CALL PP(T,DT,DEG,DEG1,XMUG,HV,CP)
      IF(X-0.)22,21,22
   21 RGI=0.
      GO TO 23
   22 CALL HOLDUP(WT,X,T,S,RLI,RGI,P)
   23 DET=(1.-RGI)*DEL+RGI*DEG
      TO=T+DT
      XO=X+DX
      SO=S+DS
      CALL HOLDUP(WT,XO,TO,SO,RLO,RGO,P)
      CALL XDEL(SO,TO,DEL1)
      DET1=(1.-RGO)*DEL1+RGO*DEG1
      DETM=(DET+DET1)/2.
      DPP=-DETM*DZ-1.*GPRF*DZ-DETM*V*DV/32.2
      A=(P+DPP)*760.0/(144.0*14.7)
      TX=(1656.39/(7.9484-ALOG10(A)))-224.92
      TX=9.0*TX/5.0+32.0
C     ****CHANGE CARD FOR BOILING POINT ELEVATION****
      BPE=.19*S*9./5.
      DT=TX+BPE-T
      CALL XCL(S,T,CL)
      B=DETM*V*C1*3600./(3.14*DP*DZ)
    1 C=(1.-X)*CL*DT+HV*DX+X*CP*DT+V*DV/(32.2*778.17)+DZ/(778.17)
      Q=B*C
      IF(TR.EQ.2.) GO TO 2
      CALL UAF(T,S,DT,DS,Q,RG,U,WT,X,DX)
      GO TO 3
    2 CALL UNB(T,S,P,DT,DS,DPP,Q,U,WT,X,DX)
    3 Q=U*(TS-T-DT/2.)
      DX1=(Q/B-(1.-X)*CL*DT-X*CP*DT-V*DV/(32.2*778.17)-DZ/778.17)/HV
      IF(ABS(DX-DX1)-.(003)6,6,5
    5 DX=(DX+DX1)/2.
   11 FORMAT(60(1H*))
      GO TO 1
    6 DX=(DX+DX1)/2.
      WG=WT*X
      WL=WT-WG
      DS=(S*WT*DX)/(WL-WT*DX)
      TO=T+DT
      XO=X+DX
      SO=S+DS
      PO=P+DPP
      CALL HOLDUP(WT,XO,TO,SO,RLO,RGO,PO)
      CALL PP(T,DT,DEG,DEG1,XMUG,HV,CP)
      CALL XDEL(SO,TO,DEL1)
      DET1=(1.-RGO)*DEL1+RGO*DEG1
      DD=DET1-DET
      DV1=-V*DD/DET
      IF(ABS(DV-DV1)-.(01)8,8,9
    9 DV=DV1
```

```
      GO TO 10
   8  DV=(DV+DV1)/2.
      RETURN
      END
$IBFTC PRF
C*************************************************************&
C*****CACULATION OF TWO PHASE FRICTIONAL PRESSURE DROP*******
C*************************************************************&
      SUBROUTINE PRF(WT,X,T,S,DX,DT,DS,GPRF,RG,P)
      COMMON C1,TS,DP
      COMMON/LEVEL2/DZ
      T=T+DT/2.0
      X=X+DX/2.
      S=S+DS/2.0
      CALL MUL(S,T,XMUL)
      CALL XDEL(S,T,DEL)
      CALL PP(T,DT,DEG,DEG1,XMUG,HV,CP)
      WG=X*WT
      WL=WT-WG
      REG=4.0*WG/(3.14*DP*XMUG)
      REL=4.0*WL/(3.14*DP*XMUL)
      A=WL/WG
      B=DEG/DEL
      C=XMUL/XMUG
      IF(REG-2100.)3,1,1
   1  IF(REL-8000.)3,2,2
   2  VM=(WL/DEL+WG/DEG)/C1
      H=.19*A**.9*B**.5*C**.1*(VM**2./(DP*32.2))**0.185
      GO TO 7
   3  IF(REG-2000.)6,4,4
   4  IF(REL-2000.)6,5,5
   5  H=SQRT(A**1.8*B*C**0.2)
   7  PG=EXP(1.54623+0.48518*ALOG(H)+0.0444*(ALOG(H))**2)
      PL=PG/H
      CL=0.046
      XN=0.2
      D=ALOG(H)
      CALL HOLDUP(WT,X,T,S,RL,RG,P)
      ALPA=RL**4.*PL**3.33
      GO TO 14
   6  IF(REG-2000.)10,8,8
   8  IF(REL-2000.)9,10,10
   9  CL=16.0
      CG=0.046
      XN=1.0
      H=SQRT((CL/CG)*REG**(-0.8)*A*B*C)
      D=ALOG(H)
      PG=EXP(1.36397+0.49115*D+0.05209*D**2)
      PL=PG/H
      CALL HOLDUP(WT,X,T,S,RL,RG,P)
      ALPA=RL**2.0*PL**2.0
      GO TO 14
  10  IF(REG-2000.)11,13,13
  11  IF(REL-2000.)13,12,12
  12   CL=0.046
```

```
      CG=16.0
      XN=0.2
      H=SQRT((CL/CG)*REL**(0.8)*A*B*C)
      D=ALOG(H)
      PG=EXP(1.35883+0.52153*D+0.05963*D**2-.0013*D**3-.0004*D**4.)
      PL=PG/H
      CALL HOLDUP(WT,X,T,S,RL,RG,P)
      ALPA=RL**4.*PL**3.33
      GO TO 14
  13  H=SQRT(A*B*C)
      CL=16.0
      XN=1.0
      D=ALOG(H)
      PG=EXP(1.0705+.5520*D+.0881*D**2-.0026*D**3-.0012*D**4)
      PL=PG/H
      CALL HOLDUP(WT,X,T,S,RL,RG,P)
      ALPA=RL**2.0*PL**2.0
  14  E=SQRT(ALPA/RL)
      F=2.*(4.*WL/3.14)**(2.-XN)*CL*XMUL**XN/(DP**(5.-XN)*DEL*32.2)
      G=ALPA**(XN-2.)*E**(5.-XN)
      GPRF=F*G
      PRD=GPRF*DZ
      T=T-DT/2.
      X=X-DX/2.
      S=S-DS/2.
      RETURN
      END
£IBFTC HOLDUP
      SUBROUTINE HOLDUP(WT,X,T,S,RL,RG,P)
C*************************************************************&
C*****CACULATION OF VOID FRACTION IN THE TUBE*****
C*************************************************************&
      COMMON C1,DZ,TS,DP
      CALL XDEL(S,T,DEL)
      DT=0.
      C=2.*DEL*X**2
      B=DEG*(1.-X)**2-4.*DEL*X**2
      A=-2.*(DEG*(1.-X)**2-DEL*X**2)
      CALL PP(T,DT,DEG,DEG1,XMUG,HV,CP)
      D=SQRT(B**2-4.*A*C)
      RG=(-B+D)/(2.*A)
      RG1=(-B-D)/(2.*A)
      IF(RG-1.)4,5,5
   5  RG=RG1
      GO TO 3
   4  IF(RG-0.)2,3,3
   2  RG=RG1
   3  RL=1.-RG
      RETURN
      END
£IBFTC UNB
      SUBROUTINE UNB(T,S,P,DT,DS,DPP,Q,U,WT,X,DX)
C*************************************************************&
C*****CACULATES OVERALL HEAT TRANSFER COEFFICIENT FOR NUCLEAT BOILING*****
C*************************************************************&
```

```
      COMMON C1,TS,DP
      COMMON/LEVEL2/DZ
      T=T+DT/2.
      S=S+DS/2.
      P=P+DPP/2.
      CALL MUL(S,T,XMUL)
      CALL XDEL(S,T,DEL)
      CALL XCL(S,T,CL)
      CALL KL(S,T,XKL)
      CALL PP(T,DT,DEG,DEG1,XMUG,HV,CP)
      ST=35./(453.6*32.2)
      PRL=CL*XMUL*3600./XKL
      WG=WT*(X+DX/2.)
      WL=WT-WG
      REL=4.0*WL/(DP*3.14*XMUL)
      REG=4.0*WG/(DP*3.14*XMUG)
      A=DEL/DEG
      B=XMUG/XMUL
      C=XKL/DP
      H1=C*(1.3+39.*DP)*PRL**0.9*REL**.23*REG**.34*A**.25*B
      D=Q*DP/(HV*XMUL*3600.0)
      E=P*DP/ST
      F=A-1.0
      H2=C*.225*PRL**.69*D**.69*E**.31*F**.33
      IF(H1-H2)1,1,2
    1 H=H2
      GO TO 3
    2 H=H1
    3 CALL XHS(T,DT,H,G,HS)
      G=1./H+1./HS
      U=1./G
      T=T-DT/2.
      S=S-DS/2.
      P=P-DPP/2.
      RETURN
      END
£IBFTC UAF
      SUBROUTINE UAF(T,S,DT,DS,Q,RG,U,WT,X,DX)
C*************************************************************&
C*****CACULATES OVERALL HEAT TRANSFER COEFFICIENT FOR ANNULAR FILM FLOW**
C*************************************************************&
      COMMON C1,TS,DP
      COMMON/LEVEL2/DZ
      T=T+DT/2.
      S=S+DS/2.
      CALL XCL(S,T,CL)
      CALL XDEL(S,T,DEL)
      CALL PP(T,DT,DEG,DEG1,XMUG,HV,CP)
      WG=WT*(X+DX/2.)
      ST=35./(453.6*32.2)
      V=WG/(DEG*C1*RG)
      A=.012*(V*SQRT(DP*DEG/(ST*32.2)))**0.5
      B=CL*SQRT(DEL*ST*32.2/DP)
      H=A*B*3600.0*4.
    2 FORMAT(* H FOR ANNULAR FLOW= *,F16.4)
```

```
      CALL XHS(T,DT,H,Q,HS)
      G=1./H+1./HS
      U=1./G
      T=T-DT/2.
      S=S-DS/2.
      RETURN
      END
£IBFTC XHS
      SUBROUTINE XHS(T,DT,H,Q,HS)
C*************************************************************&
C*****CACULATES(STEAM SIDE+WALL)HEAT TRANSFER COEFFICIENT*****
C*************************************************************&
      COMMON C1,TS,DP
      COMMON/LEVEL1/XL
      COMMON/LEVEL2/DZ
      T=T+DT/2.
      DX=0.0083
      DM=0.1743
      DPO=0.1820
      SK=26.0
      R=1./H+DX*DP/(SK*DM)+.0025
      R=1./R
      TW=T+Q/R
      TF=TS-3.*(TS-Tw)/4.
      XMUW=.00014
      XKW=0.394/3600.0
      DEW=0.932615*62.43
      CALL PP(TS,DT,DEG,DEG1,XMUG,HV,CP)
      HO=1.13*(XKW**3.*DEW**2.*32.2*HV/(XL*XMUW*(TS-TW)))**.25
      HO=HO*3600.0
      A=DX*DP/(SK*DM)+CP/(HO*DPO)+.0025
      HS=1./A
      T=T-DT/2.
      RETURN
      END
£IBFTC PP
      SUBROUTINE PP(T,DT,DEG,DEG1,XMUG,HV,CP)
C*************************************************************&
C*****PHYSICAL PROPERTIES OF WATER VAPOR*****
C*************************************************************&
      T=5.0*(T-32.0)/9.0+273.0
      CP=(7.7+.00045*T+.2521E-05*T**2.-.8587E-09*T**3.)/18.0
      T=T-273.0
      XMUG=(91.9+0.351*T)*.672E-07
      DEG=21493.61221632-400.15672832*T+2.5991631*T**2.-.00579602*T**3.
      DEG=62.43/DEG
      HV=2799.1422976-15.3096504*T+.20634652*T**2.-.00142704*T**3.
     /+.00000353*T**4.
      HV=HV*453.5924/1054.8
      T=9.0*T/5.0+32.0
      T1=5.0*((T+DT)-32.0)/9.0
      DEG1=21493.61221632-400.15672832*T1+2.5991631*T1**2.-.00579602*
     /T1**3.
      DEG1=62.43/DEG1
      RETURN
```

```
      END
£IBFTC KL
      SUBROUTINE KL(S,T,XKL)
C*************************************************************************&
C    ****PINE-WOOD BLOCK LIQUOR THERMAL CONDUCTIVITY****
C      BAMBOO
C*************************************************************************&
      T=5.0*(T-32.0)/9.0
      XKL=0.5335426 9-.(03425*S+(.0011355+.CCCC0209*S)*T
      XKL=XKL/1.49
      T=9.0*T/5.0+32.0
      RETURN
      END
£IBFTC MUL
      SUBROUTINE MUL(S,T,XMUL)
C*************************************************************************&
C    ****PINE-WOOD BLACK LIQUOR VISCOSITY****
C*************************************************************************&
      T=5.0*(T-32.0)/9.0
      A=0.4717-0.02472*T+0.7059*10.0**(-5.C)*T**(2.0)
      B=0.06973-0.5452*10.0**(-3.0)*T+0.1656*10.0**(-5.0)*T**(2.0)
      C=0.002046+0.3183*10.0**(-4.0)*T-0.9761*10.0**(-7.0)*T**(2.0)
      D=0.5793*10.0**(-4.0)-0.6129*10.0**(-6.0)*T+0.1837*10.0**(-8.0)*T*
     /*(2.0)
      XMUL=EXP(A+B*S+C*S**(2.0)+D*S**(3.0))
      XMUL=XMUL*0.0C0672
      T=9.0*T/5.0+32.0
      RETURN
      END
£IBFTC XDEL
      SUBROUTINE XDEL(S,T,DEL)
C*************************************************************************&
C    ****PINE-WOOD BLACK LIQUOR DENSITY****
C*************************************************************************&
      T=5.0*(T-32.0)/9.0
      DEL=1007.0-0.495*T+6.0*S
      DEL=DEL*0.06243
      T=9.0*T/5.0+32.0
      RETURN
      END
£IBFTC XCL
      SUBROUTINE XCL(S,T,CL)
C*************************************************************************&
C    ****PINE-WOOD BLACK LIQUOR SPECIFIC HEAT****
C*************************************************************************&
      T=5.0*(T-32.0)/9.0
      CL=(1.0-0.0054*S)*4187.0
      CL=CL*0.000239
      T=9.0*T/5.0+32.0
      RETURN
      END
£ENTRY
25.      .50      .166
.185       274.       122.       12.        2400.
```

```
&JOB   CGG153,TIME008,PAGES020,NAME A.K.AGARWAL
&IBJOB
&IBFTC MAIN
C*************************************************************************
C*****SINGLE EVAPORATOR USING SLIP MODEL
C*****BAGGASE BLACK LIQUOR IN A CLEAN TUBE****
C*************************************************************************
      COMMON C1,TS,DP
      COMMON/LEVEL1/XL
      COMMON/LEVEL2/DZ
C     SINGLE EVAPORATOR-BAGGASE-NO RESISTENCE
       READ 16,XL,DZ,DP
       READ 17,WL,TS,TI,S,P
  16   FORMAT(3F8.4)
  17   FORMAT(5F10.3)
      WG=0.
      PRINT 110
  110 FORMAT(1H1)
      PRINT 101
  101 FORMAT(*=========INPUT=========*)
      PRINT 103,WL,TS,TI,S,P
  103 FORMAT(* WL= *,F10.3,* LB-M/SECOND*,/* TS= *,F10.3,* DEGREE F *,/*
     / T=*,F10.2,* DEGREE F *,/* SOLID CONTENT= *,F10.3,* PERCENT *,/* P
     /= *,F10.1,* LBF/SQ FT *)
      PRINT 102
  102 FORMAT(*=========OUTPUT=========*)
      NE=1
       C1=(3.14*DP**2.)/4.
       T=TI
      PRINT 1
    1 FORMAT(*=========EVAPORATOR NO 1=========*)
      CALL EVAP(WL,WG,S,T,P,NE)
       STOP
      END
&IBFTC EVAP
      SUBROUTINE EVAP(WL,WG,S,T,P,NE)
C*************************************************************************
C*****SINGLE EVAPORATOR CACULATIONS*****
C*************************************************************************
      COMMON C1,TS,DP
      COMMON/LEVEL1/XL
      COMMON/LEVEL2/DZ
      K=2
         XN=XL/DZ
       DT=0.0
       QT=0.0
      N=0
      P=P*760.0/(144.0*14.7)
      BPT=(1656.390/(7.9484-ALOG10(P)))-224.92
      P=P*144.0*14.7/760.0
      BPT=9.*BPT/5.+32.
C     ****CHANGE CARD FOR BOILING POINT ELEVATION****
      BPT=BPT+.19*S*9./5.
      IF(T-BPT)37,35,35
   37 IF(NE.EQ.2) GO TO 35
      IF(NE.EQ.3) GO TO 35
```

```
1    DZ1=DZ
      CALL EML(WL,T,S,GPRLF,U,Q,UN,DT,DT1,DPT,DZ1,TX,P)
     QT1=Q*3.14*DP*DZ1
       QT=QT+QT1
       PRINT 9
      P=P+DPT
     DPF=-GPRLF*DZ1
      PRINT 8,P,DPT,DPF
 8    FORMAT(* PRESSURE= *,F16.8,* LB/SQ FT *,//* TOTAL PRESSURE DROP=
    /*,F16.8,* LB/SQ FT *,//* FRICTIONAL PRESSURE DROP= *,F15.8,* LB/SQ
    / FT *)
 9     FORMAT(110(1H*))
      PRINT 10,WL,S,T,U,UN,Q,QT1,QT
10     FORMAT(* MASS FLOW RATE OF BLACK LIQUOR= *,F16.4,* LB-M PER SECO
    /ND *,//* SOLID CONTENT= *,F16.4,* PERCENT *,//* TEMPERATURE= *,F16
    /.4,* DEGREE FAHRENHEIT *,//* FLOW-VELOCITY= *,F16.4,* FT PER SECON
    /D *,//* OVER-ALL HEAT TRANSFER CO-EFFICIENT= *,F16.4,* BTU/HR.SQ F
    /T.DEG F *,//* HEAT FLUX= *,F16.4,* BTU/HR.SQ FT *,//* HEAT TRANSFE
    /RRED IN THE SECTION= *,F16.4,* BTU/HR *,//* TOTAL HEAT TRANSFERRED
    / UP TO THIS SECTION= *,F16.4,* BTU/HR *)
      N=N+1
     PRINT 14,TX
14    FORMAT( *BOILING POINT AT THIS PRESSURE= *,F16.4,* DEGREE  F *)
     XL=XL-DZ1
     PRINT 18,XL,DZ1
18   FORMAT(* REMAINING HEIGHT= *,F16.2,* LENGTH INCREMENT= *,F15.3)
       PRINT 13,N
13   FORMAT(* COMPUTATION FOR SECTION *,I3,* HAS BEEN COMPLETED *)
       PRINT 9
     IF(N.LT.K) GO TO 51
     IF(N.EQ.K) GO TO 52
52   PRINT 53
53   FORMAT(1H1)
     K=K+2
51   CONTINUE
     IF(T-TX)2,3,3
2    CONTINUE
     PRINT 11
11   FORMAT(* CALCULATION FOR NEXT LENGTH INCREMENT-- *)
       DT=0.0
     GO TO 1
3     PRINT 15
15    FORMAT(* CALCULATION FOR NONBOILING SECTION IS COMPLETE *)
35   PRINT 36
36   FORMAT(* THERE IS NO NONBOILING SECTION *)
C    BOILING SECTION NO=1
     K=3
     XN=XL/DZ
     N=0
     WT=WL+WG
     X=WG/WT
     V=WT/(C1*62.43)
     TR=2.0
     DP1=-40.0
     DT=0.
     CALL PP(T,DT,DEG,DEG1,XMUG,HV,CP)
```

```
      DX=225.*3.14*DP*DZ*(TS-T)/(3600.*WT*HV)
   25 DV=0.
   31 DT=0.
      DS=0.
      CALL EMC(WT,X,S,T,P,V,DX,DS,DT,DPP,DV,TR,Q,WL,WG,U,RGI,RGO)
      T=T+DT
      X=X+DX
      V=V+DV
      P=P+DPP
      S=S+DS
      CALL XDEL(S,T,DEL)
      V=WL/(DEL*G1*(1.-RGO))
      QT1=Q*3.14*DP*DZ
      QT=QT+QT1
      PRINT 9
      PRINT 28,RGI
   28 FORMAT(* VOID FRACTION AT INLET= *,F16.3)
      PRINT 26,WL,WG,X,T,V,P,S,U,Q,QT1,QT,DPP
   26 FORMAT(* WL= *,F16.4,* LB-M/SECOND *,/* WG= *,F16.4,* LBM/SECOND*,
     //* X= *,F16.4,/* T= *,F16.4,* DEGREE F *,/* V= *,F16.4,* FT/SECOND
     / *,/* PRESSURE= *,F16.4,* LBF/SQ.FT *,/* SOLID CONTENT= *,F16.4,*
     / PERCENT *,/* OVER ALL HEAT TRANSFER CO-EFFICIENT= *,F16.4,* BTU/H
     /R.SQFT.DEGREE F *,/* HEAT FLUX= *,F16.4,* BTU/HR.SQFT *,/* HEAT TR
     /ANSFERRED IN THE SECTION= *,F16.4,* BTU/HR *,/* TOTAL HEAT TRANSFE
     /RRED= *,F16.4,* BTU/HR *,/* PRESSURE DROP= *,F16.4,*  LBF/SQFT *)
      PRINT 29,RGO
   29 FORMAT(* VOID FRATION AT OUTLET= *,F16.3)
      PRINT 9
      N=N+1
      PRINT 13,N
      IF(N.LT.K) GO TO 54
      IF(N.EQ.K) GO TO 55
   55 PRINT 53
      K=K+3
   54 CONTINUE
      IF(FLOAT(N)-XN)21,24,24
   21 IF((XN-FLOAT(N))-1.)32,33,33
   32 DZ=(XN-FLOAT(N))*DZ
   33 IF(RGO-0.9) 34,30,30
   34 IF(DPP-DP1) 22,23,23
   22 IF(RGO-.8)23,30,30
   30  TR=3.
      PRINT 27
   27 FORMAT(* REGION IS ANNULAR *)
   23 DP1=DPP
      GO TO 25
   24 CONTINUE
      RETURN
      END
$IBFTC EML
      SUBROUTINE EML(WL,T,S,GPRLF,U,Q,UN,DT,DT1,DPT,DZ,TK,P)
C*********************************************************************
C*****ENERGY,MOMENTUM AND CONTINUITY EQUATIONS FOR SINGLE PHASE LIQUID***
C*********************************************************************
      COMMON C1,TS,DP
    5 CALL PRLT(WL,T,S,GPRLF,DPF,DZ)
```

```
      CALL XDEL(S,T,DEL)
      CALL XCL(S,T,CL)
      U=WL/(DEL*CI)
      DPT=-DEL*DZ-1.0*GPRLF*DZ
      DELT=TS-T
      CALL XUN(TS,T,S,UN)
      Q=UN*DELT
      R=DP/2.0
      A=Q*2.0*3.14*R*DZ/(CL*7600.0*DEL*U*CI)
      B=DZ/(7.7817*100.0*CL)
      DTI=A-B
      IF(ABS(DT-DTI)-0.1)1,1,2
    2 T=T+(DTI-DT)/2.0
      DT=DTI
      GO TO 5
    1  T=T+(DTI+DT)/4.0
      P=P+DPT
      P=P*760.0/(144.0*14.7)
      TX=(1656.390/(7.9484-ALOG10(P)))-224.92
      P=P*144.0*14.7/760.0
      P=P-DPT
      TX=9.0*TX/5.0+32.0
      TX=TX+4.0
      IF(TX-T)7,6,6
    7 IF((T-TX)-.5)6,6,8
    8 DZ=DZ*.8
      T=T-(DTI+DT)/2.
      DT=0.
      GO TO 5
    6 CONTINUE
      RETURN
      END
£IBFTC PRLT
      SUBROUTINE PRLT(WL,T,S,GPRLF,DPF,DZ)
C*************************************************************************
C*****CACULATES NONBOILING SECTION LIQUID FRICTIONAL PRESSURE DROP*****
C*************************************************************************
      COMMON CI,TS,DP
      CALL MUL(S,T,XMUL)
      CALL XDEL(S,T,DEL)
      CALL MUL(S,TS,WMUL)
      V=WL/(DEL*CI)
      RE=DEL*V*DP/XMUL
      IF(RE-2100.0)1,1,2
    1  F=16.0/RE
      F=F*(WMUL/XMUL)**0.38
      GO TO 3
    2  A=4.0*ALOG10(2.0/0.00015)
      F=(1.0/(A+2.28))**2.0
      F=F*(WMUL/XMUL)**0.17
    3  DPF=-2.0*F*DZ*V**(2.0)*DEL/(DP*32.2)
      GPRLF=-DPF/DZ
      RETURN
      END
£IBFTC XUN
      SUBROUTINE XUN(TS,T,S,UN)
```

```
C*****************************************************************
C    ****NONBOILING SECTION OVERALL HEAT TRANSFER COEFFICIENT****
C*****************************************************************
      CALL XCL(S,T,CL)
      CALL MUL(S,T,XMUL)
      CALL XDEL(S,T,DEL)
      XMUL=3600.0*XMUL
      DELT=TS-T
      UN=0.06*(CL*DELT*DEL**2.0/XMUL)**0.7
      A=1./UN
      UN=1./A
      RETURN
      END
£IBFTC EMC
      SUBROUTINE EMC(WT,X,S,T,P,V,DX,DS,DT,DPP,DV,TR,Q,WL,WG,U,RGI,RGO)
C*****************************************************************
C*****SLIP MODEL FOR ENERGY,MOMENTUM AND CONTINUITY EQUATIONS*****
C*****************************************************************
      COMMON CL,TS,DP
      COMMON/LEVEL2/DZ
   10 CALL PRF(WT,X,T,S,DX,DT,DS,GPRF,RG,P)
      CALL XDEL(S,T,DEL)
      CALL PP(T,DT,DEG,DEG1,XMUG,HV,CP)
      IF(X-0.)22,21,22
   21 RGI=0.
      GO TO 23
   22 CALL HOLDUP(WT,X,T,S,RLI,RGI,P)
   23 DET=(1.-RGI)*DEL+RGI*DEG
      TO=T+DT
      XO=X+DX
      SO=S+DS
      CALL HOLDUP(WT,XO,TO,SO,RLO,RGO,P)
      CALL XDEL(SO,TO,DEL1)
      DET1=(1.-RGO)*DEL1+RGO*DEG1
      DETM=(DET+DET1)/2.
      ACI=(1.-X)**2/(DEL*(1.-RGI))+X**2/(DEG*RGI)
      ACO=(1.-XO)**2/(DEL1*(1.-RGO))+XO**2/(DEG1*RGO)
      AM=ACO-ACI
      DPP=-DETM*DZ-GPRF*DZ-WT**2*AM/(CL**2)
      A=(P+DPP)*760.0/(144.0*14.7)
      TX=(1656.39/(7.9484-ALOG10(A)))-224.92
      TX=9.0*TX/5.0+32.0
C    ****CHANGE CARD FOR BOILING POINT ELEVATION****
      BPE=.19*S*9./5.
      DT=TX+BPE-T
      CALL XCL(S,T,CL)
      AE1=X**3/(DEG**2*RGI**2)+(1.-X)**3/(DEL**2*(1.-RGI)**2)
      AE0=XO**3/(DEG1**2*RGO**2)+(1.-XO)**3/(DEL1**2*(1.-RGO)**2)
      AE=AE0-AE1
      B=WT*3600./(3.14*DP*DZ)
    1 C=(1.-X)*CL*DT+HV*DX+X*CP*DT+AE*WT**2/(2.*32.2*778.17*CL**2)+DZ/77
     /8.17
      Q=B*C
      IF(TR.EQ.2.) GO TO 2
      CALL UAF(T,S,DT,DS,Q,RG,U,WT,X,DX)
      GO TO 3
```

```
  2    CALL UNB(T,S,P,DT,DS,DPP,Q,U,WT,X,DX)
  3    Q=U*(TS-T-DT/2.)
       DX1=(Q/B-(1.-X)*CL*DT-X*CP*DT-AE*WT**2/(2.*32.2*778.17*C1**2)-DZ/7
      /78.17)/HV
       IF(ABS(DX-DX1)-.0003)6,6,5
  5    DX=(DX+DX1)/2.
  11   FORMAT(60(1H*))
       GO TO 10
  6    DX=(DX+DX1)/2.
       WG=WT*X
       WL=WT-WG
       DS=(S*WT*DX)/(WL-WT*DX)
       RETURN
       END
$IBFTC PRF
       SUBROUTINE PRF(WT,X,T,S,DX,DT,DS,GPRF,RG,P)
C*************************************************************************
C*****CACULATION OF TWO PHASE FRICTIONAL PRESSURE DROP********
C*************************************************************************
       COMMON C1,TS,DP
       COMMON/LEVEL2/DZ
       T=T+DT/2.0
       X=X+DX/2.
       S=S+DS/2.0
       CALL MUL(S,T,XMUL)
       CALL XDEL(S,T,DEL)
       CALL PP(T,DT,DEG,DEG1,XMUG,HV,CP)
       WG=X*WT
       WL=WT-WG
       REG=4.0*WG/(3.14*DP*XMUG)
       REL=4.0*WL/(3.14*DP*XMUL)
       A=WL/WG
       B=DEG/DEL
       C=XMUL/XMUG
       IF(REG-2100.)3,1,1
  1    IF(REL-8000.)3,2,2
  2    VM=(WL/DEL+WG/DEG)/C1
       H=.19*A**.9*B**.5*C**.1*(VM**2./(DP*32.2))**0.185
       GO TO 7
  3    IF(REG-2000.)6,4,4
  4    IF(REL-2000.)6,5,5
  5    H=SQRT(A**1.8*B*C**0.2)
  7    PG=EXP(1.546223+0.495188*ALOG(H)+0.0464*(ALOG(H))**2)
       PL=PG/H
       CL=0.046
       XN=0.2
       D=ALOG(H)
       CALL HOLDUP(WT,X,T,S,RL,RG,P)
       ALPA=RL**4.*PL**3.33
       GO TO 14
  6    IF(REG-2000.)10,8,8
  8    IF(REL-2000.)9,10,10
  9    CL=16.0
       CG=0.046
       XN=1.0
       H=SQRT((CL/CG)*REG**(-0.8)*A*B*C)
```

```
      D=ALOG(H)
      PG=EXP(1.36397+0.49115*D+0.05209*D**2)
      PL=PG/H
      CALL HOLDUP(WT,X,T,S,RL,RG,P)
      ALPA=RL**2.0*PL**2.0
      GO TO 14
   10 IF(REG-2000.)11,13,13
   11 IF(REL-2000.)13,12,12
   12  CL=0.046
      CG=16.0
      XN=0.2
      H=SQRT((CL/CG)*REL**(0.8)*A*B*C)
      D=ALOG(H)
      PG=EXP(1.35883+0.52153*D+0.05963*D**2-.0013*D**3-.0004*D**4.)
      PL=PG/H
      CALL HOLDUP(WT,X,T,S,RL,RG,P)
      ALPA=RL**4.*PL**3.33
      GO TO 14
   13 H=SQRT(A*B*C)
      CL=16.0
      XN=1.0
      D=ALOG(H)
      PG=EXP(1.0705+.5520*D+.0881*D**2-.0026*D**3-.0012*D**4)
      PL=PG/H
      CALL HOLDUP(WT,X,T,S,RL,RG,P)
      ALPA=RL**2.0*PL**2.0
   14 E=SQRT(ALPA/RL)
      F=2.*(4.*WL/3.14)**(2.*XN)*CL*XMUL**XN/(DP**(5.-XN)*DEL**2.2)
      G=ALPA**(XN-2.)*E**(5.-XN)
      GPRF=F*G
      PRD=GPRF*DZ
      T=T-DT/2.
      X=X-DX/2.
      S=S-DS/2.
      RETURN
      END
£IBFTC HOLDUP
      SUBROUTINE HOLDUP(WT,X,T,S,RL,RG,P)
C**********************************************************************
C*****CACULATION OF VOID FRACTION IN THE TUBE******
C**********************************************************************
      COMMON CL,DZ,TS,DP
      CALL XDEL(S,T,DEL)
      DT=0.
      CALL PP(T,DT,DEG,DEG1,XMUG,HV,CP)
      A=-2.*(DEG*(1.-X)**2+DEL*X**2)
      B=DEG*(1.-X)**2-4.*DEL*X**2
      C=2.*DEL*X**2
      D=SQRT(B**2-4.*A*C)
      RG=(-B+D)/(2.*A)
      RG1=(-B-D)/(2.*A)
      IF(RG-1.)4,5,5
    5 RG=RG1
      GO TO 3
    4 IF(RG-0.)2,3,3
    2 RG=RG1
```

```
    3   RL=1.-RG
        RETURN
        END
$IBFTC UNB
        SUBROUTINE UNB(T,S,P,DT,DS,DPP,Q,U,WT,X,DX)
C*************************************************************
C*****CACULATES OVERALL HEAT TRANSFER COEFFICIENT FOR NUCLEAT BOILING***
C*************************************************************
        COMMON CL,TS,DP
        COMMON/LEVEL2/DZ
        T=T+DT/2.
        S=S+DS/2.
        P=P+DPP/2.
        CALL MUL(S,T,XMUL)
        CALL XDEL(S,T,DEL)
        CALL XCL(S,T,CL)
        CALL KL(S,T,XKL)
        CALL PP(T,DT,DEG,DEGI,XMUG,HV,CP)
        ST=35./(453.6*32.2)
        PRL=CL*XMUL*3600./XKL
        WG=WT*(X+DX/2.)
        WL=WT-WG
        REL=4.0*WL/(DP*3.14*XMUL)
        REG=4.0*WG/(DP*3.14*XMUG)
        A=DEL/DEG
        B=XMUG/XMUL
        C=XKL/DP
        H1=C*(1.3+39.*DP)*PRL**0.9*REL**.23*REG**.34*A**.25*B
        D=Q*DP/(HV*XMUL*3600.0)
        E=P*DP/ST
        F=A-1.0
        H2=C*.225*PRL**.69*D**.69*E**.31*F**.33
        IF(H1-H2)1,1,2
    1   H=H2
        GO TO 3
    2   H=H1
    3   CALL XHS(T,DT,H,Q,HS)
        G=1./H+1./HS
        U=1./G
        T=T-DT/2.
        S=S-DS/2.
        P=P-DPP/2.
        RETURN
        END
$IBFTC UAF
        SUBROUTINE UAF(T,S,DT,DS,Q,RG,U,WT,X,DX)
C*************************************************************
C*****CACULATES OVERALL HEAT TRANSFER COEFFICIENT FOR ANNULAR FILM FLOW***
C*************************************************************
        COMMON CL,TS,DP
        COMMON/LEVEL2/DZ
        T=T+DT/2.
        S=S+DS/2.
        CALL XCL(S,T,CL)
        CALL XDEL(S,T,DEL)
        CALL PP(T,DT,DEG,DEGI,XMUG,HV,CP)
```

```
      WG=WT*(X+DX/2.)
      ST=35./(453.5*32.2)
      V=WG/(DEG*CL*RG)
      A=.012*(V*SQRT(DP*DEG/(ST*32.2)))**0.5
      B=CL*SQRT(DEL*ST*32.2/DP)
      H=A*B*3600.0*4.
    2 FORMAT(* H FOR ANNULAR FLOW= *,F16.4)
      CALL XHS(T,DT,H,Q,HS)
      G=1./H+1./HS
      U=1./G
      T=T-DT/2.
      S=S-DS/2.
      RETURN
      END
$IBFTC XHS
      SUBROUTINE XHS(T,DT,H,Q,HS)
C*************************************************************
C*****CACULATES(STEAM SIDE+WALL)HEAT TRANSFER COEFFICIENT*****
C*************************************************************
      COMMON CL,TS,DP
      COMMON/LEVEL1/XL
      COMMON/LEVEL2/DZ
      T=T+DT/2.
      DX=0.0083
      DM=0.1745
      DPO=0.1820
      SK=26.0
      R=1./H+DX*DP/(SK*DM)
      R=1./R
      TW=T+Q/R
      TF=TS-3.*(TS-TW)/4.
      TF=5.*(T-32.)/9.
      XMUW=.00014
      XKW=.394/3600.
      DEW=.932615*62.43
      CALL PP(TS,DT,DEG,DEGI,XMUG,HV,CP)
      HO=1.13*(XKW**3.*DEW**2.*32.2*HV/(XL*XMUW*(TS-TW)))**.25
      HO=HO*3600.0
      A=DX*DP/(SK*DM)+DP/(HO*DPO)
      HS=1./A
      T=T-DT/2.
      RETURN
      END
$IBFTC PP
      SUBROUTINE PP(T,DT,DEG,DEGI,XMUG,HV,CP)
C*************************************************************
C*****PHYSICAL PROPERTIES OF WATER VAPOR*****
C*************************************************************
      T=5.0*(T-32.0)/9.0+273.0
      CP=(7.7+.00045*T+.2521E 05*T**2.-.8587E-09*T**3.)/18.0
      T=T-273.0
      XMUG=(91.9+0.351*T)*.672E-07
      DEG=21493.61221632+500.15672832*T+2.5991631*T**2.-.00579602*T**3.
      DEG=62.43/DEG
      HV=2799.1422976-15.309604*T+.20634452*T**2.-.00142704*T**3.
     /+.00000388*T**4.
```

```
      HV=HV*453.5924/1054.8
      T=9.0*T/5.0+32.0
      T1=5.0*((T+DT)-32.0)/9.0
      DEG1=21493.61221632-400.15672832*T1+2.5991631*T1**2.-.0057960Z*
     /T1**3.
      DEG1=62.43/DEG1
      RETURN
      END
£IBFTC MUL
      SUBROUTINE MUL(S,T,XMUL)
C*************************************************************************
C    ****BAGGASE BLACK LIQUOR VISCOSITY****
C*************************************************************************
      T=5.*(T-32.)/9.
      A=18.276186-.507619*T+.00343*T**2
      B=-1.427423+.043054*T-.0003074*T**2
      C=.032877-.000898*T+.0000064*T**2
      XMUL=EXP(A+B*S+C*S**2)
      XMUL=XMUL*.000672
      T=9.*T/5.+32.
      RETURN
      END
£IBFTC XDEL
      SUBROUTINE XDEL(S,T,DEL)
C*************************************************************************
C    ****BAGGASE BLACK LIQUOR DENSITY****
C*************************************************************************
      T=5.*(T-32.)/9.
      DEL=1.0207+.0071*S+T*(-.000279-.0000012*S)
      DEL=DEL*62.43
      T=9.*T/5.+32.
      RETURN
      END
£IBFTC XCL
      SUBROUTINE XCL(S,T,CL)
C*************************************************************************
C    ****BAGGASE BLACK LIQUOR SPECFIC HEAT****
C*************************************************************************
      T=5.*(T-32.)/9.
      CL=.993-.01258*S+T*(.0000556+.00010*S)
      T=9.*T/5.+32.
      RETURN
      END
£IBFTC KL
      SUBROUTINE KL(S,T,XKL)
C*************************************************************************
C    ****BAGGASE BLACK LIQUOR THERMAL CONDUCTIVITY****
C*************************************************************************
      T=5.*(T-32.)/9.
      XKL=.50576-.00268*S+T*(.000899+.00000749*S)
      XKL=XKL/1.49
      T=9.*T/5.+32.
      RETURN
      END
£ENTRY
25.      .50      .166
```

```
£JOB    CGG155,TIME010,PAGES025,NAME R.P.SHLKLA
£IBJOB
£IBFTC MAIN
C*****THIS USES SLIP MODEL FOR BADGER,S DATA SIMULATION                  AKAOOC1O
C       BADGER,S DATA SIMULATION                                        AKAOOO11
        COMMON C1,TS,DP                                                 AKAOOO2O
        COMMON/LEVEL1/XL                                                AKAOOO3O
        COMMON/LEVEL2/DZ                                                AKAOOO4O
        DO 2 I=1,15                                                     AKAOOO5O
         READ 16,XL,DZ,DP                                               AKAOOO6O
  16     FORMAT(3F8.4)                                                  AKAOOO7O
         READ 17,WL,TS,TI,S,P                                           AKAOOO8O
  17   FORMAT(5F10.4)                                                   AKAOOO9O
       PRINT 3,I                                                        AKAOO1OO
  3    FORMAT(* BADGER DATA NO ---- *,I3)                               AKAOO11O
       WG=0.                                                            AKAOO12O
       PRINT 101                                                        AKAOO13O
  101  FORMAT(*-----------------------------INPUT-------------------------------*)  AKAOO14O
       PRINT 103,WL,TS,TI,S,P                                           AKAOO15O
  103  FORMAT(* WL= *,F10.3,* LB-M/SECOND*,/* TS= *,F10.3,* DEGREE F *,/*AKAOO16O
      / T=*,F10.2,* DEGREE F *,/* SOLID CONTENT= *,F10.3,* PERCENT *,/* PAKAOO17O
      /= *,F10.3,* LBF/SQ FT *)                                         AKAOO18O
       PRINT 102                                                        AKAOO19O
  102  FORMAT(*-----------------------------OUTPUT--------------------------------*)  AKAOO2CO
       NE=1                                                             AKAOO21O
        C1=(3.14*DP**2.)/4.                                             AKAOO22O
        T=TI                                                            AKAOO23O
       CALL EVAP(WL,WG,S,T,P,NE)                                        AKAOO24O
  2    CONTINUE                                                         AKAOO25O
        STOP                                                            AKAOO26O
       END                                                              AKAOO27O
£IBFTC EVAP                                                             AKAOO28O
       SUBROUTINE EVAP(WL,WG,S,T,P,NE)                                  AKAOO29O
C*****SINGLE EVAPORATOR CACULATIONS*******                              AKAOO3OO
       COMMON C1,TS,DP                                                  AKAOO3O1
       COMMON/LEVEL1/XL                                                 AKAOO31O
       COMMON/LEVEL2/DZ                                                 AKAOO32O
          XN=XL/DZ                                                      AKAOO33O
        DT=0.0                                                          AKAOO34O
        QT=0.0                                                          AKAOO35O
       N=0                                                              AKAOO36O
       CALL VPT(P,BPT)                                                  AKAOO37O
       BPT=BPT+.19*S*9./5.                                              AKAOO38O
       IF(T-BPT)37,35,35                                                AKAOO39O
  37   IF(NE.EQ.2) GO TO 35                                             AKAOO4OO
       IF(NE.EQ.3) GO TO 35                                             AKAOO41O
  1    DZ1=DZ                                                           AKAOO42O
        CALL EML(WL,T,S,GPRLF,U,Q,UN,DT,DT1,DPT,DZ1,TX,P)               AKAOO43O
       QT1=Q*3.14*DP*DZ1                                                AKAOO44O
         QT=QT+QT1                                                      AKAOO45O
         PRINT 9                                                        AKAOO46O
        P=P+DPT                                                         AKAOO47O
      DPF=-GPRLF*DZ1                                                    AKAOO48O
      PRINT 8,P,DPT,DPF                                                 AKAOO49O
   8    FORMAT(* PRESSURE= *,F16.8,* LB/SQ FT *,//* TOTAL PRESSURE DROP= AKAOO5OO
```

```
     /*,F16.8,* LB/SQ FT *,//* FRICTIONAL PRESSURE DROP= *,F16.8,* LB/SQAKA00710
     / FT *)                                                          AKA00720
   9   FORMAT(110(1H-))                                               AKA00730
       PRINT10,WL,S,T,U,UN,Q,QT1,QT                                   AKA00731
  10     FORMAT(* MASS FLOW RATE OF BLACK LIQUOR= *,F16.4,* LB-M PER SECOAKA00740
     /ND *,//* SOLID CONTENT= *,F16.4,* PERCENT *,//* TEMPERATURE= *,F16AKA00750
     /.4,* DEGREE FAHRENHEIT *,//* FLOW-VELOCITY= *,F16.4,* FT PER SECONAKA00760
     /D *,//* OVER-ALL HEAT TRANSFER CO-EFFICIENT= *,F16.4,* BTU/HR.SQ FAKA00770
     /T.DEG F *,//* HEAT FLUX= *,F16.4,* BTU/HR.SQ FT *,//* HEAT TRANSFEAKA00780
     /RRED IN THE SECTION= *,F16.4,* BTU/HR *,//* TOTAL HEAT TRANSFERREDAKA00790
     / UP TO THIS SECTION= *,F16.4,* BTU/HR *)                        AKA00800
       N=N+1                                                          AKA00810
       PRINT 14,TX                                                    AKA00811
  14   FORMAT( *BOILING POINT AT THIS PRESSURE= *,F16.4,* DEGREE  F *)  AKA00820
       XL=XL-DZ1                                                      AKA00830
       PRINT 18,XL,DZ1                                                AKA00840
  18   FORMAT(* REMAINING HEIGHT= *,F16.2,* LENGTH INCREMENT= *,F16.3)  AKA00850
       PRINT 13,N                                                     AKA00851
  13   FORMAT(* COMPUTATION FOR SECTION *,I3,* HAS BEEN COMPLETED *)    AKA00860
       IF(T-TX)2,3,3                                                  AKA00870
   2   CONTINUE                                                       AKA00880
       PRINT 11                                                       AKA00881
  11   FORMAT(* CALCULATION FOR NEXT LENGTH INCREMENT-- *)            AKA00890
       DT=0.0                                                         AKA00900
       GO TO 1                                                        AKA00910
   3   PRINT 15                                                       AKA00920
  15   FORMAT(* CALCULATION FOR NONBOILING SECTION IS COMPLETE *)     AKA00930
  35   PRINT 36                                                       AKA00940
  36   FORMAT(* THERE IS NO NONBOILING SECTION *)                     AKA00950
C      BOILING SECTION NO-1                                           AKA00960
       XN=XL/DZ                                                       AKA00970
       N=0                                                            AKA00980
       US = 0.                                                        AKA00990
       HTB=0.                                                         AKA01000
       ST=0.                                                          AKA01010
       WT=WL+WG                                                       AKA01020
       X=WG/WT                                                        AKA01030
       V=WT/(C1*62.43)                                                AKA01040
       TR=2.0                                                         AKA01050
       DP1=-40.0                                                      AKA01060
       DT=0.                                                          AKA01070
       CALL PP(T,DT,DEG,DEG1,XMUG,HV,CP)                              AKA01080
       DX=400.*3.14*DP*DZ*(TS-T)/(3600.*WT*HV)                        AKA01090
  25   DV=0.                                                          AKA01100
  31   DT=0.                                                          AKA01110
       DS=0.                                                          AKA01120
       CALL EMC(WT,X,S,T,P,V,DX,DS,DT,DPP,DV,TR,Q,WL,WG,U,RGI,RGO)    AKA01130
       T=T+DT                                                         AKA01140
       X=X+DX                                                         AKA01150
       V=V+DV                                                         AKA01160
       P=P+DPP                                                        AKA01170
       S=S+DS                                                         AKA01180
       QT1=Q*3.14*DP*DZ                                               AKA01190
       QT=QT+QT1                                                      AKA01200
       US=US+U                                                        AKA01210
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      HTB=HTB+QT1                                                       AKA01020
      PRINT 9                                                           AKA01021
      PRINT 28,RGI                                                      AKA01022
                                                                        AKA01030
      PRINT 26,WL,WG,X,T,V,P,S,U,Q,QT1,QT,DPP                           AKA01031
   28 FORMAT(* VOID FRACTION AT INLET= *,F16.3)                         AKA01040
   26 FORMAT(* WL= *,F16.4,* LB-M/SECOND *,/* WG= *,F16.4,* LBM/SECOND*,AKA01050
     //* X= *,F16.4,/* T= *,F16.4,* DEGREE F *,/* V= *,F16.4,* FT/SECONDAKA01060
     / *,/* PRESSURE= *,F16.4,* LBF/SQ.FT *,/* SOLID CONTENT= *,F16.4,* AKA01070
     / PERCENT *,/* OVER ALL HEAT TRANSFER CO-EFFICIENT= *,F16.4,* BTU/HAKA01080
     /R.SQFT.DEGREE F *,/* HEAT FLUX= *,F16.4,* BTU/HR.SQFT *,/* HEAT TRAKA01090
     /ANSFERRED IN THE SECTION= *,F16.4,* BTU/HR *,/* TOTAL HEAT TRANSFEAKA01100
     /RRED= *,F16.4,* BTU/HR *,/* PRESSURE DROP= *,F16.4,*  LBF/SQFT *) AKA01110
      PRINT 29,RGO                                                      AKA01111
   29 FORMAT(* VOID FRATION AT OUTLET= *,F16.3)                         AKA01120
      PRINT 9                                                           AKA01121
      N=N+1                                                             AKA01130
      PRINT 13,N                                                        AKA01131
      IF(FLOAT(N)-XN)21,24,24                                           AKA01140
   21 IF((XN-FLOAT(N))-1.)32,33,33                                      AKA01150
   32 DZ=(XN-FLOAT(N))*DZ                                               AKA01160
   33 IF(RGO-0.9) 34,34,30                                              AKA01170
   34 IF(DPP-DP1) 22,23,23                                              AKA01180
   22 IF(RGO-.8)23,30,30                                                AKA01190
   30  TR=3.                                                            AKA01200
      PRINT 27                                                          AKA01201
   27 FORMAT(* REGION IS ANNULAR *)                                     AKA01210
   23 DP1=DPP                                                           AKA01220
      GO TO 25                                                          AKA01230
   24 CONTINUE                                                          AKA01240
      US=US/FLOAT(N)                                                    AKA01250
      US2=FLOAT(N)*HTB/(3.14*DP*XL*ST)                                  AKA01260
      PRINT 41,US,US2                                                   AKA01270
   41 FORMAT(* AVERAGE BOILING HEAT TRANSFER COEFFICIENT= *,2F16.2)     AKA01280
      PRINT 42 ,HTB                                                     AKA01290
   42 FORMAT(* HEAT TRANSFERRED IN THE BOILING SECTION = *,F16.2)       AKA01300
      WG=WG*3600.                                                       AKA01310
      PRINT 43,WG,P                                                     AKA01320
   43 FORMAT(* VAPOR COLLECTED = *,F16.1,* PRESSUR = *,F16.2)           AKA01330
      RETURN                                                            AKA01340
      END                                                               AKA01350
£IBFTC EML                                                              AKA01360
      SUBROUTINE EML(WL,T,S,GPRLF,U,Q,UN,DT,DT1,DPT,DZ,TX,P)            AKA01370
C*****ENERGY,MOMENTUM AND CONTINUITY EQUATIONS FOR SINGLE PHASE LIQUID**AKA01371
      COMMON C1,TS,DP                                                   AKA01380
    5 CALL PRLT(WL,T,S,GPRLF,DPF,DZ)                                    AKA01390
      CALL XDEL(S,T,DEL)                                                AKA01400
      CALL XCL(S,T,CL)                                                  AKA01410
      U=WL/(DEL*C1)                                                     AKA01420
      DPT=-DEL*DZ-1.0*GPRLF*DZ                                          AKA01430
      DELT=TS-T                                                         AKA01440
      CALL XUN(TS,T,S,UN)                                               AKA01450
      Q=UN*DELT                                                         AKA01460
      R=DP/2.0                                                          AKA01470
      A=Q*2.0*3.14*R*DZ/(CL*3600.0*DEL*U*C1)                            AKA01480
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      B=DZ/(7.7817*100.0*CL)                                              AKA01490
      DT1=A-B                                                             AKA01500
      IF(ABS(DT-DT1)-0.1)1,1,2                                            AKA01510
    2 T=T+(DT1-DT)/2.0                                                    AKA01520
      DT=DT1                                                              AKA01530
      GO TO 5                                                             AKA01540
    1  T=T+(DT1+DT)/4.0                                                   AKA01550
      P=P+DPT                                                             AKA01560
      CALL VPT(P,TX)                                                      AKA01570
      P=P-DPT                                                             AKA01580
      IF(TX-T)7,6,6                                                       AKA01590
    7 IF((T-TX)-.5)6,6,8                                                  AKA01600
    8 DZ=DZ*.8                                                            AKA01610
      T=T-(DT1+DT)/2.                                                     AKA01620
      DT=0.                                                               AKA01630
      GO TO 5                                                             AKA01640
    6 CONTINUE                                                            AKA01650
      RETURN                                                              AKA01660
      END                                                                 AKA01670
£IBFTC PRLT                                                               AKA01680
      SUBROUTINE PRLT(WL,T,S,GPRLF,DPF,DZ)                                AKA01690
C*****CACULATES NONBOILING SECTION LIQUID FRICTIONAL PRESSURE DROP****    AKA01691
      COMMON C1,TS,DP                                                     AKA01700
      CALL MUL(S,T,XMLL)                                                  AKA01710
      CALL XDEL(S,T,DEL)                                                  AKA01720
      CALL MUL(S,TS,WMUL)                                                 AKA01730
      V=WL/(DEL*C1)                                                       AKA01740
      RE=DEL*V*DP/XMUL                                                    AKA01750
      IF(RE-2100.0)1,1,2                                                  AKA01760
    1 F=16.0/RE                                                           AKA01770
      F=F*(WMUL/XMUL)**0.38                                               AKA01780
      GO TO 3                                                             AKA01790
    2 A=4.0*ALOG10(2.0/0.00025)                                           AKA01800
      F=(1.0/(A+2.28))**2.0                                               AKA01810
      F=F*(WMUL/XMUL)**0.17                                               AKA01820
    3 DPF=2.0*F*DZ*V**(2.0)*DEL/(DP*32.2)                                 AKA01830
      GPRLF=-DPF/DZ                                                       AKA01840
      RETURN                                                              AKA01850
      END                                                                 AKA01860
£IBFTC XUN                                                                AKA01870
      SUBROUTINE XUN(TS,T,S,UN)                                           AKA01880
C   ****NONBOILING SECTION OVERALL HEAT TRANSFER COEFFICIENT****          AKA01881
      CALL XCL(S,T,CL)                                                    AKA01890
      CALL MUL(S,T,XMLL)                                                  AKA01900
      CALL XDEL(S,T,DEL)                                                  AKA01910
      XMUL=3600.0*XMUL                                                    AKA01920
      DELT=TS-T                                                           AKA01930
      UN=0.06*(CL*DELT*DEL**2.0/XMUL)**0.7                                AKA01940
      A=1./UN                                                             AKA01950
      UN=1./A                                                             AKA01960
      RETURN                                                              AKA01970
      END                                                                 AKA01980
£IBFTC EMC                                                                AKA01990
      SUBROUTINE EMC(WT,X,S,T,P,V,DX,DS,DT,DPP,DV,TR,Q,WL,WG,U,RGI,RGO)   AKA02000
C*****SLIP MODEL FOR ENERGY,MOMENTUM AND CONTINUITY EQUATIONS*****        AKA02001
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      COMMON C1,TS,DP                                                   AKA02C1C
      COMMON/LEVEL2/DZ                                                  AKA02C2C
   10 CALL PRF(WT,X,T,S,DX,DT,DS,GPRF,RG,P)                             AKA02C3C
      CALL XDEL(S,T,DEL)                                                AKA02C4C
      CALL PP(T,DT,DEG,DEG1,XMUG,HV,CP)                                 AKA02C5C
      IF(X-0.)22,21,22                                                  AKA02C6C
   21 RGI=0.                                                            AKA02C7C
      GO TO 23                                                          AKA02C8C
   22 CALL HOLDUP(WT,X,T,S,RLI,RGI,P)                                   AKA02C9C
   23 DET=(1.-RGI)*DEL+RGI*DEG                                          AKA02100
      TO=T+DT                                                           AKA02110
      XO=X+DX                                                           AKA02120
      SO=S+DS                                                           AKA02130
      CALL HOLDUP(WT,XO,TO,SO,RLO,RGO,P)                                AKA02140
      CALL XDEL(SO,TO,DEL1)                                             AKA02150
      DET1=(1.-RGO)*DEL1+RGO*DEG1                                       AKA02160
      DETM=(DET+DET1)/2.                                                AKA02170
      ACI=(1.-X)**2/(DEL*(1.-RGI))+X**2/(DEG*RGI)                       AKA02180
      ACO=(1.-XO)**2/(DEL1*(1.-RGO))+XO**2/(DEG1*RGO)                   AKA02190
      AM=ACO-ACI                                                        AKA02200
      DPP=-DETM*DZ-GPRF*DZ-WT**2*AM/(C1**2)                             AKA02210
      A=P+DPP                                                           AKA02220
      CALL VPT(A,TX)                                                    AKA02230
      BPE=.19*S*9./5.                                                   AKA02240
      DT=TX+BPE-T                                                       AKA02250
      CALL XCL(S,T,CL)                                                  AKA02260
      AEI=X**3/(DEG**2*RGI**2)+(1.-X)**3/(DEL**2*(1.-RGI)**2)           AKA02270
      AEO=XO**3/(DEG1**2*RGO**2)+(1.-XO)**3/(DEL1**2*(1.-RGO)**2)       AKA02280
      AE=AEO-AEI                                                        AKA02290
      B=WT*3600./(3.14*DP*DZ)                                           AKA02300
    1 C=(1.-X)*CL*DT+HV*DX+X*CP*DT+AE*WT**2/(2.*32.2*778.17*C1**2)+DZ/7AKA02310
     /8.17                                                              AKA02320
      Q=B*C                                                             AKA02330
      IF(TR.EQ.2.) GO TO 2                                              AKA02340
      CALL UAF(T,S,DT,DS,Q,RG,U,WT,X,DX)                                AKA02350
      GO TO 3                                                           AKA02360
    2 CALL UNB(T,S,P,DT,DS,DPP,Q,U,WT,X,DX)                             AKA02370
    3 Q=U*(TS-T-DT/2.)                                                  AKA02380
      DX1=(Q/B-(1.-X)*CL*DT-X*CP*DT-AE*WT**2/(2.*32.2*778.17*C1**2)-DZ/7AKA02390
     /8.17)/HV                                                          AKA02400
      IF(ABS(DX-DX1)-.(C03)6,6,5                                        AKA02410
    5 DX=(DX+DX1)/2.                                                    AKA02420
   11 FORMAT(60(1H*))                                                   AKA02430
      GO TO 10                                                          AKA02440
    6 DX=(DX+DX1)/2.                                                    AKA02450
      WG=WT*X                                                           AKA02460
      WL=WT-WG                                                          AKA02470
      DS=(S*WT*DX)/(WL-WT*DX)                                           AKA02480
      RETURN                                                            AKA02490
      END                                                               AKA02500
£IBFTC PRF                                                              AKA02510
      SUBROUTINE PRF(WT,X,T,S,DX,DT,DS,GPRF,RG,P)                       AKA02520
C*****CACULATION OF TWO PHASE FRICTIONAL PRESSURE DROP*******           AKA02521
      COMMON C1,TS,DP                                                   AKA02530
      COMMON/LEVEL2/DZ                                                  AKA02540
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      T=T+DT/2.0                                                        AKAO2750
      X=X+DX/2.                                                         AKAO2760
      S=S+DS/2.0                                                        AKAO2770
      CALL MUL(S,T,XMUL)                                                AKAO2780
      CALL XDEL(S,T,DEL)                                                AKAO2790
      CALL PP(T,DT,DEG,DEG1,XMUG,HV,CP)                                 AKAO2800
      WG=X*WT                                                           AKAO2810
      WL=WT-WG                                                          AKAO2820
      REG=4.0*WG/(3.14*DP*XMUG)                                         AKAO2830
      REL=4.0*WL/(3.14*DP*XMUL)                                         AKAO2840
      A=WL/WG                                                           AKAO2850
      B=DEG/DEL                                                         AKAO2860
      C=XMUL/XMUG                                                       AKAO2870
      IF(REG-2100.)3,1,1                                                AKAO2880
    1 IF(REL-8000.)3,2,2                                                AKAO2890
    2 VM=(WL/DEL+WG/DEG)/C1                                             AKAO2900
      H=.19*A**.9*B**.5*C**.1*(VM**2./(DP*32.2))**0.185                 AKAO2910
      GO TO 7                                                           AKAO2920
    3 IF(REG-2000.)6,4,4                                                AKAO2930
    4 IF(REL-2000.)6,5,5                                                AKAO2940
    5 H=SQRT(A**1.8*B*C**0.2)                                           AKAO2950
    7 PG=EXP(1.54623+0.48518*ALOG(H)+0.0444*(ALOG(H))**2)               AKAO2960
      PL=PG/H                                                           AKAO2970
      CL=0.046                                                          AKAO2980
      XN=0.2                                                            AKAO2990
      D=ALOG(H)                                                         AKAO3000
      CALL HOLDUP(WT,X,T,S,RL,RG,P)                                     AKAO3010
      ALPA=RL**4.*PL**3.33                                              AKAO3020
      GO TO 14                                                          AKAO3030
    6 IF(REG-2000.)10,8,8                                               AKAO3040
    8 IF(REL-2000.)9,11,10                                              AKAO3050
    9 CL=16.0                                                           AKAO3060
      CG=0.046                                                          AKAO3070
      XN=1.0                                                            AKAO3080
      H=SQRT((CL/CG)*REG**(-0.8)*A*B*C)                                 AKAO3090
      D=ALOG(H)                                                         AKAO3100
      PG=EXP(1.36397+0.49115*D+0.05209*D**2)                            AKAO3110
      PL=PG/H                                                           AKAO3120
      CALL HOLDUP(WT,X,T,S,RL,RG,P)                                     AKAO3130
      ALPA=RL**2.0*PL**2.0                                              AKAO3140
      GO TO 14                                                          AKAO3150
   10 IF(REG-2000.)11,13,13                                             AKAO3160
   11 IF(REL-2000.)13,12,12                                             AKAO3170
   12  CL=0.046                                                         AKAO3180
      CG=16.0                                                           AKAO3190
      XN=0.2                                                            AKAO3200
      H=SQRT((CL/CG)*REL**(0.8)*A*B*C)                                  AKAO3210
      D=ALOG(H)                                                         AKAO3220
      PG=EXP(1.35883+0.52153*D+0.05963*D**2-.0013*D**3-.0004*D**4.)     AKAO3230
      PL=PG/H                                                           AKAO3240
      CALL HOLDUP(WT,X,T,S,RL,RG,P)                                     AKAO3250
      ALPA=RL**4.*PL**3.33                                              AKAO3260
      GO TO 14                                                          AKAO3270
   13 H=SQRT(A*B*C)                                                     AKAO3280
      CL=16.0                                                           AKAO3290
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      XN=1.0                                                                    AKA03 CC
      D=ALOG(H)                                                                 AKA03 1C
      PG=EXP(1.0705+.552C*D+.0881*D**2-.0026*D**3-.0012*D**4)                   AKA03 2C
      PL=PG/H                                                                   AKA03 3C
      CALL HOLDUP(WT,X,T,S,RL,RG,P)                                             AKA03 4C
      ALPA=RL**2.0*FL**2.0                                                      AKA03 5C
   14 E=SQRT(ALPA/RL)                                                           AKA03 6C
      F=2.*(4.*WL/3.14)**(2.-XN)*CL*XMUL**XN/(DP**(5.-XN)*DEL*32.2)             AKA03 7C
      G=ALPA**(XN-2.)*E**(5.-XN)                                                AKA03 8C
      GPRF=F*G                                                                  AKA03 9C
      PRD=GPRF*DZ                                                               AKA032CC
      T=T-DT/2.                                                                 AKA0321C
      X=X-DX/2.                                                                 AKA0322C
      S=S-DS/2.                                                                 AKA0323C
      RETURN                                                                    AKA0324C
      END                                                                       AKA0325C
IBFTC HOLDUP                                                                    AKA0326C
      SUBROUTINE HOLDUP(WT,X,T,S,RL,RG,P)                                       AKA0327C
*****CACULATION OF VOID FRACTION IN THE TUBE*****                               AKA03271
      COMMON C1,DZ,TS,DP                                                        AKA0328C
      CALL XDEL(S,T,DEL)                                                        AKA0329C
      DT=0.                                                                     AKA033CC
      CALL PP(T,DT,DEG,DEG1,XMUG,HV,CP)                                         AKA0331C
      A=-2.*(DEG*(1.-X)**2-DEL*X**2)                                            AKA0332C
      B=DEG*(1.-X)**2-4.*DEL*X**2                                               AKA0333C
      C=2.*DEL*X**2                                                             AKA0334C
      D=SQRT(B**2-4.*A*C)                                                       AKA0335C
      RG=(-B+D)/(2.*A)                                                          AKA0336C
      RG1=(-B-D)/(2.*A)                                                         AKA0337C
      IF(RG-1.)4,5,5                                                            AKA0338C
    5 RG=RG1                                                                    AKA0339C
      GO TO 3                                                                   AKA034CC
    4 IF(RG-0.)2,3,3                                                            AKA0341C
    2 RG=RG1                                                                    AKA0342C
    3 RL=1.-RG                                                                  AKA0343C
      RETURN                                                                    AKA0344C
      END                                                                       AKA0345C
IBFTC UNB                                                                       AKA0346C
      SUBROUTINE UNB(T,S,P,DT,DS,DPP,Q,U,WT,X,DX)                               AKA0347C
*****CACULATES OVERALL HEAT TRANSFER COEFFICIENT FOR NUCLEAT BOILING***        AKA03471
      COMMON C1,TS,DP                                                           AKA0348C
      COMMON/LEVEL2/DZ                                                          AKA0349C
      T=T+DT/2.                                                                 AKA035CC
      S=S+DS/2.                                                                 AKA0351C
      P=P+DPP/2.                                                                AKA0352C
      CALL MUL(S,T,XMUL)                                                        AKA0353C
      CALL XDEL(S,T,DEL)                                                        AKA0354C
      CALL XCL(S,T,CL)                                                          AKA0355C
      CALL KL(S,T,XKL)                                                          AKA0356C
      CALL PP(T,DT,DEG,DEG1,XMUG,HV,CP)                                         AKA0357C
      T=(T-32.)*5./9.                                                           AKA0358C
      ST=75.83076-0.148356*T-.00021*T**2                                        AKA0359C
      ST=ST/(493.6*32.2)                                                        AKA036CC
      T=9.*T/5.+32.                                                             AKA0361C
      PRL=CL*XMUL*3600./XKL                                                     AKA0362C
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      WG=WT*(X+DX/2.)                                                    AKAC3430
      WL=WT-WG                                                           AKAC3440
      REL=4.0*WL/(DP*3.14*XMUL)                                          AKAC3450
      REG=4.0*WG/(DP*3.14*XMUG)                                          AKAC3460
      A=DEL/DEG                                                          AKAC3470
      B=XMUG/XMUL                                                        AKAC3480
      C=XKL/DP                                                           AKAC3490
      H1=C*(1.3+39.*DP)*PRL**0.9*REL**.23*REG**.24*A**.25*B              AKAC3700
      D=Q*DP/(HV*XMUL*3600.0)                                            AKAC3710
      E=P*DP/ST                                                          AKAC3720
      F=A-1.0                                                            AKAC3730
      H2=C*.225*PRL**.69*D**.79*E**.31*F**.33                            AKAC3740
      IF(H1-H2)1,1,2                                                     AKAC3750
    1 H=H2                                                               AKAC3760
      GO TO 3                                                            AKAC3770
    2 H=H1                                                               AKAC3780
    3 CALL XHS(T,DT,H,G,HS)                                              AKAC3790
      G=1./H+1./HS                                                       AKAC3800
      U=1./G                                                             AKAC3810
      T=T-DT/2.                                                          AKAC3820
      S=S-DS/2.                                                          AKAC3830
      P=P-DPP/2.                                                         AKAC3840
      RETURN                                                             AKAC3850
      END                                                                AKAC3860
$IBFTC UAF                                                               AKAC3870
      SUBROUTINE UAF(T,S,DT,DS,Q,RG,U,WT,X,DX)                           AKAC3880
C*****CACULATES OVERALL HEAT TRANSFER COEFFICIENT FOR ANNULAR FILM FLOW* AKAC3881
      COMMON C1,TS,DP                                                    AKAC3890
      COMMON/LEVEL2/DZ                                                   AKAC3900
      T=T+DT/2.                                                          AKAC3910
      S=S+DS/2.                                                          AKAC3920
      CALL XCL(S,T,CL)                                                   AKAC3930
      CALL XDEL(S,T,DEL)                                                 AKAC3940
      CALL PP(T,DT,DEG,DEG1,XMUG,HV,CP)                                  AKAC3950
      WG=WT*(X+DX/2.)                                                    AKAC3960
      T=(T-32.)*5./9.                                                    AKAC3970
      ST=75.83076-0.148356*T-.00021*T**2                                 AKAC3980
      ST=ST/(453.6*32.2)                                                 AKAC3990
      T=9.*T/5.+32.                                                      AKAC4000
      V=WG/(DEG*C1*RG)                                                   AKAC4010
      A=.012*(V*SQRT(DF*DEG/(ST*32.2)))**0.5                             AKAC4020
      B=CL*SQRT(DEL*ST*32.2/DP)                                          AKAC4030
      H=A*B*3600.0*4.                                                    AKAC4040
C*****CACULATES(STEAM SIDE+WALL)HEAT TRANSFER COEFFICIENT*****          AKAC4141
    2 FORMAT(* H FOR ANNULAR FLOW= *,F16.4)                              AKAC4050
      CALL XHS(T,DT,H,G,HS)                                              AKAC4060
      G=1./H+1./HS                                                       AKAC4070
      U=1./G                                                             AKAC4080
      T=T-DT/2.                                                          AKAC4090
      S=S-DS/2.                                                          AKAC4100
      RETURN                                                             AKAC4110
      END                                                                AKAC4120
$IBFTC XHS                                                               AKAC4130
      SUBROUTINE XHS(T,DT,H,Q,HS)                                        AKAC4140
      COMMON C1,TS,DP                                                    AKAC4150
```

```
      COMMON/LEVEL1/XL                                                  AKA04150
      COMMON/LEVEL2/DZ                                                  AKA04170
      T=T+DT/2.                                                         AKA04180
      DX=.0095                                                          AKA04190
      DM=.1565                                                          AKA04200
      DP0=.166                                                          AKA04210
      SK=218.0                                                          AKA04220
      R=1./H+DX*DP/(SK*DM)                                              AKA04230
      R=1./R                                                            AKA04240
      TW=T+Q/R                                                          AKA04250
      TF=TS-3.*(TS-TW)/4.                                               AKA04260
      XKW=.394/3600.                                                    AKA04270
      CALL MUL(S,TF,XMLW)                                               AKA04280
      DEW=.97*62.43                                                     AKA04290
      CALL PP(TS,DT,DEG,DEG1,XMUG,HV,CP)                                AKA04300
      HO=1.13*(XKW**3.*DEW**2.*32.2*HV/(XL*XMUW*(TS-TW)))**.25          AKA04310
      HO=HO*3600.0                                                      AKA04320
      A=DX*DP/(SK*DM)+DP/(HO*DP0)                                       AKA04330
      HS=1./A                                                           AKA04340
      T=T-DT/2.                                                         AKA04350
      RETURN                                                            AKA04360
      END                                                               AKA04370
£IBFTC PP                                                               AKA04380
      SUBROUTINE PP(T,DT,DEG,DEG1,XMUG,HV,CP)                           AKA04390
C**&**PSYSICAL PROPERTIES OF WATER VAPOR*****                           AKA04391
      T=5.0*(T-32.0)/9.0+273.0                                          AKA04400
      CP=(7.7+.00045*T+.2521E-05*T**2.-.8587E-09*T**3.)/18.0            AKA04410
      T=T-273.0                                                         AKA04420
      XMUG=(91.9+0.351*T)*.672E-07                                      AKA04430
      DEG=21493.61221632-400.15672832*T+2.5991631*T**2.-.00579602*T**3. AKA04440
      DEG=62.43/DEG                                                     AKA04450
      HV=2799.1422976-15.3096504*T+.20634452*T**2.-.00142704*T**3.      AKA04460
     /+.00000353*T**4.                                                  AKA04470
      HV=HV*453.5924/154.8                                              AKA04480
      T=9.0*T/5.0+32.0                                                  AKA04490
      T1=5.0*((T+DT)-32.0)/9.0                                          AKA04500
      DEG1=21493.61221632-400.15672832*T1+2.5991631*T1**2.-.00579602*   AKA04510
     /T1**3.                                                            AKA04520
      DEG1=62.43/DEG1                                                   AKA04530
      RETURN                                                            AKA04540
      END                                                               AKA04550
£IBFTC KL                                                               AKA04560
      SUBROUTINE KL(S,T,XKL)                                            AKA04570
C     WATER                                                             AKA04580
C**&**WITER THERMAL CONDUCTIVITY****                                    AKA04581
      T=5.0*(T-32.0)/9.0                                                AKA04590
      XKL=587.*(1.+2.81*.001*(T-20.))                                   AKA04600
      XKL=XKL*2.389/4190.                                               AKA04610
      T=9.0*T/5.0+32.0                                                  AKA04620
      RETURN                                                            AKA04630
      END                                                               AKA04640
£IBFTC MUL                                                              AKA04650
      SUBROUTINE MUL(S,T,XMUL)                                          AKA04660
C     WATER                                                             AKA04670
C*****WATER VISCOSITY*****                                              AKA04671
```

```
      T=5.*(T-32.)/9.                                                    AKA04680
      XMUL=1.996531-.0160284*T+.00006745*T**2                            AKA04690
      XMUL=XMUL*.000672                                                  AKA04700
      T=9.*T/5.+32.                                                      AKA04710
      RETURN                                                             AKA04720
      END                                                                AKA04730
£IBFTC XDEL                                                              AKA04740
      SUBROUTINE XDEL(S,T,DEL)                                           AKA04750
C     WATER                                                              AKA04760
C*****WATER DENSITY****                                                  AKA04761
      DEL=.97*62.43                                                      AKA04770
      RETURN                                                             AKA04780
      END                                                                AKA04790
£IBFTC XCL                                                               AKA04800
      SUBROUTINE XCL(S,T,CL)                                             AKA04810
C     WATER                                                              AKA04820
C*****WATER SPECIFIC HEAT*******                                         AKA04821
      CL=1.0                                                             AKA04830
      RETURN                                                             AKA04840
      END                                                                AKA04850
£IBFTC VPT                                                               AKA04860
      SUBROUTINE VPT(P,T)                                                AKA04870
C*****PRESSURE TEMPERATURE EQUATION FOR WATER****                        AKA04871
      P=P*760./(144.*14.7)                                               AKA04880
      IF(P.LT.30..AND.P.GT.5.) GO TO 2                                   AKA04890
      IF(P.LT.35..AND.P.GT.30.) GO TO 3                                  AKA04900
      IF(P.LT.90..AND.P.GT.35.) GO TO 4                                  AKA04910
      IF(P.LT.150..AND.P.GT.90.) GO TO 5                                 AKA04920
      IF(P.LT.230..AND.P.GT.150.) GO TO 6                                AKA04930
      IF(P.LT.340..AND.P.GT.230.) GO TO 7                                AKA04940
      IF(P.LT.520..AND.P.GT.340.) GO TO 8                                AKA04950
      IF(P.LT.760..AND.P.GT.520.) GO TO 9                                AKA04960
      IF(P.GT.760.) GO TO 10                                             AKA04970
    2 A=8.184254                                                         AKA04980
      B=1791.3                                                           AKA04990
      C=238.1                                                            AKA05000
      GO TO 1                                                            AKA05010
    3 A=8.1393986                                                        AKA05020
      B=1767.262                                                         AKA05030
      C=236.29                                                           AKA05040
      GO TO 1                                                            AKA05050
    4 A=8.0886767                                                        AKA05060
      B=1739.351                                                         AKA05070
      C=234.1                                                            AKA05080
      GO TO 1                                                            AKA05090
    5 A=8.0464202                                                        AKA05100
      B=1715.429                                                         AKA05110
      C=232.14                                                           AKA05120
      GO TO 1                                                            AKA05130
    6 A=8.0116295                                                        AKA05140
      B=1695.167                                                         AKA05150
      C=230.41                                                           AKA05160
      GO TO 1                                                            AKA05170
    7 A=7.9845588                                                        AKA05180
      B=1678.948                                                         AKA05190
```

```
      C=228.97                                                          AKAC52CC
      GO TO 1                                                           AKAC5210
    8 A=7.9634288                                                       AKAC5220
      B=1665.924                                                        AKAC5230
      C=227.77                                                          AKAC5240
      GO TO 1                                                           AKAC5250
    9 A=7.948396                                                        AKAC5260
      B=1656.39                                                         AKAC5270
      C=226.86                                                          AKAC5280
      GO TO 1                                                           AKAC5290
   10 A=7.9186968                                                       AKAC53CC
      B=1636.909                                                        AKAC5310
      C=224.92                                                          AKAC5320
    1 T=(B/(A-ALOG10(P)))-C                                             AKAC5330
      T=9.*T/5.+32.                                                     AKAC5340
      P=P*144.*14.7/760.                                                AKAC5350
      RETURN                                                            AKAC5360
      END                                                               AKAC5370
£ENTRY
20.       0.5       0.147
0.066       209.75      162.1       0.0          1230.
```

```
-------------------------------INPUT-------------------------------
WL=     0.066  LB-M/SECOND
TS=209.75  DEGREE F
T=  162.10  DEGREE F
SOLID CONTENT=  0.000 PERCENT
P=1230.000  LBF/SQ FT
------------------------------OUTPUT-------------------------------
REMAINING HEIGHT=    17.74   LENGTH INCREMENT= 0.256
CACULATION FOR NONBOILING SECTION IS COMPLETE
THERE IS NO NONBOILING SECTION
AVERAGE BOILING HEAT TRANSFER COEFFICIENT= 470.90   472.41
HEAT TRANSFERRED IN THE BOILING SECTION=  149627.89
VAPOR COLLECTED= 151.7      PRESSURE= 253.08
```

```
$JOB    CGG153,TIME008,PAGES020,NAME A.K.AGARWAL
$IBJOB
$IBFTC MAIN
C*****************************************************************
C*****THIS USES SLIP MODEL FOR BADGER,S DATA SIMULATION
C*****THIS PROGRAMME USES BOELTER EQUATION FOR NONBOILING HEAT TRANSFER
C*****************************************************************
      COMMON C1,TS,DP
      COMMON/LEVEL1/XL
      COMMON/LEVEL2/DZ
       READ 16,XL,DZ,DP
       READ 17,WL,TS,TI,S,P
   16   FORMAT(3F8.4)
   17  66RMAT(5F10.3)
      WG=0.
      PRINT 110
  110 FORMAT(1H1)
      P9INT 101
    1   66RMAT&*------ -------- --------INPUT----------------------*)
      P9INT  03,WL,TS,TI,S,P
    1 3 66RMAT(* WL= *,F10.3,* LB-M/SECOND*,/* TS= *,F10.3,* DEGREE F *,/*
     / T=*,F10.2,* DEGREE F *,/* SOLID CONTENT= *,F10.3,* PERCENT *,/* P
     /= *,F10.3,* LBF/SQ FT *)
      PRINT 102
  102 FORMAT(*----------------------OUTPUT-------------------------*)
      NE=1
       C1=(3.14*DP**2.)/4.
       T=TI
      PRINT 1
    1   FORMAT(*-----------------EVAPORATOR NO 1--------------------*)
        LL ESAP(WL,WG,S,T,P,NE)
       STOP
      554
$IBFTC EVAP
C*****&&*&*&&*****************************************************
C*****SINGLE EVAPORATOR CACULATIONS*****
C*****************************************************************
      SUBROUTINE EVAP(WL,WG,S,T,P,NE)
      COMMON C1,TS,DP
      C6MMON LEVEL1/XL
      COMMON/LEVEL2/DZ
      K=2
      XN=XL/DZ
       DT=0.0
       QT=0.0
      N=0
      3A3L V7T(P,BPT)
      BPT=BPT+.19*S*9./5.
      IF(T-BPT)37,35,35
   37   IF(NE.EQ.2) GO TO 35
      IF(NE.EQ.3) GO TO 35
    1   DZ1=DZ
        CALL EML(WL,T,S,GPRLF,U,Q,UN,DT,DT1,DPT,DZ1,TX,P)
      QT1=Q*3.14*DP*DZ1
        QT=QT+QT1
        PRINT 9.
```

```
      P=P+DPT
      DPF=-G7RLF*DZ1
      PRINT 8,P,DPT,DPF
    8 FORMAT(* PRESSURE= *,F16.8,* LB/SQ FT *,//* TOTAL PRESSURE DROP=
     /*=F16.8,* LB/SQ FT *,//* FRICTIONAL PRESSURE DROP= *,F16.8,* LB/SQ
     / FT *)
    9 6ORMAT(110(1H-))
      P9INT 10,WL,S,T,U,UN,Q,QT1,QT
   10  FORMAT(* MASS FLOW RATE OF BLACK LIQUOR= *,F16.4,* LB-M PER SECO
     /N4 *,//* SOLID CONTENT= *,F16.4,* PERCENT *,//* TEMPERATURE= *,F16
     /.4,* DEGREE FAHRENHEIT *,//* F3OW-VE-OCITY= *,F16.4,* FT PER SECON
     /4 &,//& OVER-ALL HEAT TRANSFER CO-EFFICIENT= *,F16.4,* BTU/HR.SQ F
     /T.DEG F *,//* HEAT FLUX= *,F16.4,* BTU/HR.SQ FT *,//* HEAT TRANSFE
     /RRED IN THE SECTION= *,F16.4,* BTU/8R *,//* TOTAL HEAT T9ANSFERRED
     / UP TO THIS SECTION= *,F16.4,* BTU/HR *)
      N=N+1
      799NT 14,TX
   14  FORMAT( *BOILING POINT AT THIS PRESSURE= *,F16.4,* DEGREE  F *)
      XL=XL-DZ1
      P9INT  8,XL,DZ1
   18 FORMAT(* REMAINING HEI7HT= *,F16=2,* LENGTH INCREMENT= *,F16.3)
      PRINT 13,N
   13 FORMAT(* COMPUTATION FOR SE3TI6N *,I3,* HAS BEEN COMPLETED *)
      PRINT 9
      IF(N.LT.K) GO TO 51
      IF(N.EQ.K) GO TO 52
   52 PRINT 53
   53 FORMAT(1H1)
      K=K+2
   51 CONTINUE
      IF(T-TX)2,3,3
    2 CONTINUE
      79INT  1
   11 FORMAT(* CALCULATION FOR NEXT LENGTH INCREMENT-- *)
      DT=0.0
      GO TO 1
    3  7RINT 15
    1   6RMAO(* CALCULATION FOR NONBOILING SECTION IS COMPLETE *)
   35 P9INT 36
   36 66RMAT(* THERE IS NO NONBOILING SECTION *)
      BOILING SECTION NO=1
      K=3
      X5=XL/+Z
      N=0
      US = 0.
      HTB=0.
      ST=0.
      WT=WL+WG
      X=WG/WT
      V=WT/(C1*62.43)
      TR=2.0
      DP1=-40.0
      D0=0.
      3+3L PP(T,DT,D G,DEG1,XMUG,HV,CP)
      DX=400.*3.14*DP*DZ*(TS-T)/(3600.*WT*HV)
   25 DV=0.
```

```
 31   DT=0.
      DS=0.
      CALL EMC(WT,X,S,T,P,V,DX,DS,DT,DPP,DV,TR,Q,WL,WG,U,RGI,RGO)
      T=T+DT
      X=X+DX
      V=V+DV
      P=P+DPP
      S=S+DS
      CALL XDEL(S,T,DEL)
      V=WL/(DEL*C1*(1.-RGO))
      QT1=Q*3.14*DP*4Z
      QT=QT+QT1
      US=US+U
      HTB=HTB+QT1
      ST=ST+TS-T+DT/2.
      PRINT 9
      PRINT 28,RGI
 28   FORMAT(* VOID FRACTION AT INLET= *,F16.3)
      PRINT 26,WL,WG,X,T,V,P,S,U,Q,QT1,QT,DPP
 26   FORMAT(* WL= *,F16.4,* LB-M/SECOND *,/* WG= *,F16.4,* LBM/SECOND*,
     //* X= *,F16.4,/* T= *,F16.4,* DEGREE F *,/* V= *,F16.4,* FT/SECOND
     / *,/* PRESSURE= *,F16.4,* LBF/SQ.FT *,/* SOLID CONTENT= *,F16.4,*
     / PERCENT *,/* OVER ALL HEAT TRANSFER CO-EFFICIENT= *,F16.4,* BTU/H
     /R.SQFT.DEGREE F *,/* HEAT FLUX= *,F16.4,* BTU/HR.SQFT *,/* HEAT TR
     /ANSFERRED IN THE SECTION= *,F16.4,* BTU/HR *,/* TOTAL HEAT TRANSFE
     /RRED= *,F16.4,* BTU/HR *,/* PRESSURE DROP= *,F16.4,*  LBF/SQFT *)
      PRINT 29,RGO
 29   FORMAT(* VOID FRATION AT OUTLET= *,F16.3)
      PRINT 9
      N=N+1
      PRINT 13,N
      IF(N.LT.K) GO TO 54
      IF(N.EQ.K) GO TO 55
 55   PRINT 53
      K=K+3
 54   CONTINUE
      IF(FLOAT(N)-XN)21,24,24
 21   IF((XN-FLOAT(N))-1.)32,33,33
 32   DZ=(XN-FLOAT(N))*DZ
 33   IF(RGO-0.9) 34,30,30
 34   IF(DPP-DP1) 22,23,23
 22   IF(RGO-.8)23,30,30
 30    TR=3.
      PRINT 27
 27   FORMAT(* REGION IS ANNULAR *)
 23   DP1=DPP
      GO TO 25
 24   CONTINUE
      US=US/FLOAT(N)
      US2=FLOAT(N)*HTB/(3.14*DP*XL*ST)
      PRINT 41,US,US2
 41   FORMAT(* AVERAGE BOILING HEAT TRANSFER COEFFICIENT= *,2F16.2)
      PRINT 42 ,HTB
 42   FORMAT(* HEAT TRANSFERRED IN THE BOILING SECTION = *,F16.2)
      RETURN
      END
```

```
£IBFTC EML
C*******************************************************************************
C*****ENERGY,MOMENTUM AND CONTINUITY EQUATIONS FOR SINGLE PHASE LIQUID*****
C*******************************************************************************
      SUBROUTINE EML(WL,T,S,GPRLF,U,Q,UN,DT,DT1,DPT,DZ,TX,P)
      COMMON C1,TS,DP
  5   CALL PRLT(WL,T,S,GPRLF,DPF,DZ)
       CALL XDEL(S,T,DEL)
       CALL XCL(S,T,CL)
      U=WL/(DEL*C1)
       DPT=-DEL*DZ-1.0*GPRLF*DZ
       DELT=TS-T
      CALLXUN(WL,T,S,DT,UN)
       Q=UN*DELT
      R=DP/2.0
       A=Q*2.0*3.14*R*DZ/(CL*2600.0*DEL*U*C1)
      B=DZ/(7.7817*100.0*CL)
      DT1=A-B
      IF(ABS(DT-DT1)-0.1)1,1,2
  2   T=T+(DT1-DT)/2.0
      DT=DT1
      GO TO 5
  1    T=T+(DT1+DT)/4.0
      P=P+DPT
      CALL VPT(P,TX)
      P=P-DPT
      IF(TX-T)7,6,6
  7   IF((T-TX)-.5)6,6,8
  8   DZ=DZ*.8
      T=T-(DT1+DT)/2.
      DT=0.
      GO TO 5
  6   CONTINUE
      RETURN
       END
£IBFTC PRLT
C*******************************************************************************
C*****CACULATES NONBOILING SECTION LIQUID FRICTIONAL PRESSURE DROP*****
C*******************************************************************************
      SUBROUTINE PRLT(WL,T,S,GPRLF,DPF,DZ)
      COMMON C1,TS,DP
       CALL MUL(S,T,XMUL)
       CALL XDEL(S,T,DEL)
       CALL MUL(S,TSYWMUL)
       V=WL/(DEL*C1)
      RE=DEL*V*DP/XMUL
       IF(RE-2100.0)1,1,2
  1    F=16.0/RE
       F=F*(WMUL/XMUL)**0.38
      GO TO 3
  2    A=4.0*ALOG10(2.0/0.00015)
      F=(1.0/(A+2.28))**2.0
      F=F*(WMUL/XMJL)**0.17
  3    DPF=-2.0*F*DZ*V**(2.0)*DEL/(DP*32.2)
       GPRLF=-DPF/DZ
      RETURN
```

```
      END
$IBFTC XUN
C*******************************************************************
C    ****NONBOILING SECTION OVERALL HEAT TRANSFER COEFFICIENT****
C*******************************************************************
      SUBROUTINE XUN(WL,T,S,DT,UN)
      COMMON CL,TS,DP
      CALL XCL(S,T,CL)
      CALL MUL(S,T,XMUL)
      CALL XDEL(S,T,DEL)
      CALL KL(S,T,XKL)
      XL=3.2
      TF=123.03
      H1=250.
      TF=5.*(TF-32.)/9.
      TW=TS-.05*TS
    5 TW=5.*(TW-32.)/9.
      BETA=(.000162*(TW-TF)+.0000031*(TW**2-TF**2))*5./((.9962245+.0001
     /612*TF**2+.0000031*TF**2)*(TW-TF)*9.)
      TF=9.*TF/5.+32.
      TW=9.*TW/5.+32.
   10 XNU=H1*DP/XKL
      GZM=3600.*WL*CL/(XKL*XL)
      A=3.14*XNU/GZM
      B=ALOG((2.+A)/(2.-A))
      F1=A/B
      IF(A.LT.1.85) GO TO 1
      IF(A.LT.2.) GO TO 2
      F2=0.
      GO TO 3
    1 F2=1.-.408*A
      GO TO 3
    2 F2=-1.63*(A-2.)
    3 C=32.2*DP**4*BETA*(TW-TF)*3600.*DEL**2*CL/(XMUL*XKL*XL)
      XNU=1.75*F1*(GZM+.0722*F2*C**.84)**.33
      H2=XNU*XKL/DP
      IF(ABS(H1-H2).LT.5.) GO TO 4
      H1=H2
      GO TO 10
    4 H=(H1+H2)/2.
      CALL XHS(T,DT,H,Q,HS)
      G=1./H+1./HS
      UN=1./G
      RETURN
      END
$IBFTC EMC
C*******************************************************************
C*****SLIP MODEL FOR ENERGY,MOMENTUM AND CONTINUITY EQUATIONS*****
C*******************************************************************
      SUBROUTINE EMC(WT,X,S,T,P,V,DX,DS,DT,DPP,DV,TR,Q,WL,WG,U,RGI,RGD)
      COMMON CL,TS,DP
      COMMON/LEVEL2/DZ
   10 CALL PRF(WT,X,T,S,DX,DT,DS,GPRF,RG,P)
      CALL XDEL(S,T,DEL)
      CALL PP(T,DT,DEG,DEGI,XMUG,HV,CP)
      IF(X-0.)22,21,22
```

```
 21   RGI=0.
      GO TO 23
 22   CALL HOLDUP(WT,X,T,S,RLI,RGI,P)
 23   DET=(1.-RGI)*DEL+RGI*DEG
      TO=T+DT
      XO=X+DX
      SO=S+DS
      CALL HOLDUP(WT,XO,TO,SO,RLO,RGO,P)
      CALL XDEL(SO,TO,DEL1)
      DET1=(1.-RGO)*DEL1+RGO*DEG1
      DETM=(DET+DET1)/2.
      ACI=(1.-X)**2/(DEL*(1.-RGI))+X**2/(DEG*RGI)
      ACO=(1.-XO)**2/(DEL1*(1.-RGO))+XO**2/(DEG1*RGO)
      AM=ACO-+CI
      DPP=-DETM*DZ-GPRF*DZ-WT**2*AM/(C1**2)
      A=P+DPP
      CALL VPT(A,TX)
      BPE=.19*S*9./5.
      DT=TX+BPE-T
      CALL XCL(S,T,CL)
      AE1=X**3/(DEG**2*RGI**2)+(1.-X)**3/(DEL**2*(1.-RGI)**2)
      AEO=XO**3/(DEG1**2*RGO**2)+(1.-XO)**3/(DEL1**2*(1.-RGO)**2)
      AE=AEO-AEI
      B=WT*3600./(3.14*DP*DZ)
 1    C=(1.-X)*CL*DT+HV*DX+X*CP*DT+AE*WT**2/(2.*32.2*778.17*C1**2)+DZ/77
     /8.17
      Q=B*C
      IF(TR.5Q.2.) GO TO 2
      CALL UAF(T,S,DT,DS,Q,RG,U,WT,X,DX)
      GO TO 3
 2    CALL UNB(T,S,P,DT,DS,DPP,Q,U,WT,X,DX)
 3    Q=U*(TS-T-DT/2.)
      DX1=(Q/B-(1.-X)*CL*DT-X*CP*DT-AE*WT**2/(2.*32.2*778.17*C1**2)-DZ/7
     /78.17)/8V
      IF(ABS(DX-DX1)-.0003)6,6,5
 5    DX=(DX+DX1)/2.
 11   FORMAT(60(1H*H)
      GO TO 10
 6    DX=(DX+DX1)/2.
      WG=WT*X
      WL=WT-WG
      DS=(S*WT*DX)/(WL-WT*DX)
      RETURN
      END
£IBFTC PRF
C*************************************************************************
C**&**3ACULATION OF TWO PHASE FRICTIONAL PRESSURE DROP*******
C*************************************************************************
      SUBROUTINE PRF(WT,X,T,S,DX,DT,DS,GPRF,RG,P)
      COMMON C1,TS,DP
      COMMON/LEVEL2/DZ
      T=T+DT/2.0
      X=X+DX/2.
      S=S+DS/2.0
      CALL MUL(S,T,XMUL)
      CALL XDEL(S,T,DEL)
```

```
      CALL PP(T,DT,DEG,DEG1,XMUG,HV,CP)
      WG=X*WT
      WL=WT-WG
      REG=4.0*WG/(3.14*DP*XMUG)
      REL=4.0*WL/(3.14*DP*XMUL)
      A=WL/W7
      B=DEG/DEL
      C=XMUL/XMUG
      IF(REG-2100.)3,1,1
    1 IF(REL-8000.)3,2,2
    2 VM=(WL/DEL+WG/DEG)/C1
      H=.19*A**.9*3**.5*C**.1*(VM**2./(DP*32.2))**0.185
      GO TO 7
    3 IF(REG-2000.)6,4,4
    4 IF(REL-2000.)6,5,5
    5 H=SQRT(1**1.8*B*C**0.2&
    7 PG=EXP(1.54623+0.48518*ALOG(H)+0.0444*(ALOG(H))**2)
      PL=PG/H
      CL=0.046
      XN=0.2
      D=ALOG(H)
      CALL HOLDUP(WT,X,T,S,RL,RG,P)
      AL7A=RL**4.*PL**3.33
      GO TO 14
    6 IF(REG-2000.)10,8,8
    8 IF(REL-2000.)9,10,10
    9 CL=16.0
      CG=0.046
      XN=1.0
      H=SQRT((CL/CG)*REG**(-.8)*A*B*C)
      D=ALOG(8)
      PG=EXP(1.36397+0.49115*D+0.05209*D**2)
      PL=PG/H
      CALL HO-DUP(WT,X,T,S,RL,RG,P)
      ALPA=RL**2.0*PL**2.0
      GO TO 14
   10 IF(REG-2000.)11,13,13
   11 IF(REL-2000.)13,12,12
   12  CL=0.046
      CG=16.0
      X5=0.2
      H=SQRT((CL/CG)*REL**(0.8)*A*B*C)
      D=ALOG(H)
      PG=EXP(1.35883 0.52153*D+0.05963*D**2-.0013*D**3-.0004*D**4.)
      PL=PG/H
      CALL HOLDUP(WT,X,T,S,RL,RG,P)
      ALPA=RL**4.*PL**3.33
      GO TO 14
   13 H=SQRT(A*B*C)
      CL=16.0
      XN=1.0
      D=ALOG(H)
      PG=EXP(1.0705+.5520*D+.0881*D**2-.0026*D**3-.0012*D**4)
      PL=PG/H
      CALL HOLDUP(WT,X,T,S,RL,RG,P)
      ALPA=RL**2.0*PL**2.0
```

```
  14   E=SQRT(ALPA/RL)
       F=2.*(4.*WL/3.14)**(2.-XN)*CL*XMUL**XN/(DP**(5.-XN)*DEL*32.2)
       G=ALPA**(XN-2.)*E**(5.-XN)
       GPRF=F*G
       PRD=GPRF*DZ
       T=T-DT/2.
       X=X-DX/2.
       S=S-DS/2.
       RETURN
       END
£IBFTC HOLDUP
C*************************************************************************
C*****CACULATION OF VOID FRACTION IN THE TUBE*****
C**&**&&*****&*************************************************************
       SUBROUTINE HOLDUP(WT,X,T,S,RL,RG,P)
       COMMON C1,TS,DP
       CALL XDEL(S,T,DEL)
       DT=0.
       CALL PP(T,DT,DEG,DEG1,XMUG,HV,CP)
       A=-2.*(DEG*(1.-X)**2-DEL*X**2)
       B=DEG*(1.-X)**2-4.*DEL*X**2
       C=2.*D+L*X**2
       D=SQRT(B**2-4.*A*C)
       R7=(-2+D)/(2.*+)
       RG1=(-B-D)/(2.*A)
       IF(RG-1.)4,5,5
   5   RG=RG1
       GO TO 3
   4   IF(RG-0.)2,3,3
   2   RG=RG1
   3   RL=1.-RG
       RETURN
       END
£IBFTC UNB
C***&*********************************************************************
C*****CACULATES OVERALL HEAT TRANSFER COEFFICIENT FOR NUCLEAT BOILING***
C*************************************************************************
       SUBROUTINE UNB(T,S,P,DT,DS,DPP,Q,U,WT,X,DX)
       COMMON C1,TS,DP
       COMMON/LEVEL2/DZ
       T=T+DT/2.
       S=S+DS/2.
       P=P+DPP/2.
       CALL MUL(S,T,XMUL)
       CILL X4EL(S,T,4EL)
       CALL XCL(S,T,CL)
       CALL KL(S,T,XKL)
       CALL PP(T,DT,DEG,DEG1,XMUG,HV,CP)
       T=(T-3 .)*5./9.
       ST=75.83076-0.148356*T-.00021*T**2
       ST=ST/(468.6*32.2)
       T=9.*T/5.+32.
       793=CL*XMUL*3600./XKL
       WG=WT*(X+DX/2.)
       WL=WT-WG
       REL=4.0*WL/(DP*3.14*XMUL)
```

```
      REG=4.0*WG/(DP*3.14*XMUG)
      A=DEL/4+G
      B=XMUG/XMUL
      C=XKL/DP
      H1=C*(1.3+39.*DP)*PRL**0.9*REL**.23*REG**.34*A**.25*B
      D=Q*DP/(HV*XMUL*3600.0)
      E=P*DP/ST
      F=A-1.0
      82=C*.2 5*PRL**.69*D**.69*F*&.31*F**.33
      IF(H1-H2)1,1,2
  1   H=H2
      GO TO 3
  2   H=H1
  3   CALL XHS(T,DT,8,Q,HS)
      G=1./H+1./HS
      U=1./G
      T=T-DT/2.
      S=S-DS/2.
      P=P-D7P/2.
      RETURN
      END
£IBFTC UAF
C*************************************************************************
C*****CACULATES OVERALL HEAT TRANSFER COEFFICIENT FOR ANNJLAR FILM FLOW**
C**&***&&**&&*********************************************************
      SUBROUTINE UAF(T,S,DT,DS,Q,RG,U,WT,X,DX)
      COMMON C1,TS,DP
      C64MON/LEVEL2/DZ
      T=T+DT/2.
      S=S+DS/2.
      CALL XCL(S,T,CL)
      CALL XDEL(S,T,4EL)
      CALL PP(T,DT,DEG,DE31,XMUG,HV,CP)
      WG=WT*(X+DX/2.)
      T=(T-32.)*5./9.
      ST=75.83076-0.148356*T-.00021*T**2
      ST=ST/(453.6*32.2)
      T=9.*T/5.+32.
      5=W7/(4EG*C1*RG)
      A=.0128(V*SQRT(DP*DE3/(ST*32.2)))**0.5
      B=CL*SQRT(DE_*ST*32.2/DP)
      H8 *B*3600.0*4H
  2   FORMAT(* H FOR ANNULAR FLOW= *,F16.4)
      CALL XHS(T,DT,H,Q,HS)
      G=1./H+1./HS
      U=1./G
      T=T-DT/2.
      S=S-DS/2.
      RETURN
      END
£IB6TC 78S
C**&*************&*****************************************************
C*****CACULA3ES(STEAM SIDE+WALL)HEAT TRAN2FER COEFFICIENT*****
C*************************************************************************
      S BROU3INE XHS&T,DT,H,Q,HS)
      COMMON C1,TS,DP
```

```
      COMMON/LEVEL2/DZ
      XL=20.
      T=T+DT/2.
      DX=.0095
      DM=.1565
      DPO=.166
      SK=218.0
      R=1./H+DX*DP/(SK*DM)
      R=1./R
      IF(Q.EQ.0.) GO TO 1
      TW=T+Q/R
      GO TO 2
    1 TW=TS-.05*TS
    2 TF=TS-3.*(TS-TW)/4.
      ZKW=.394/3600.
      CALL MUL(S,TF,XMUW)
      RHOW=.97*62.43
      CALL PP(TS,DP,DEG,DEG1,XMUG,HV,CP)
      HO=1.13*(XKW**3.*DEW**2.*32.2*HV/(XL*XMUW*(TS-TW)))**.25
      HO=HO*3600.0
      A=DX*DP/(SK*DM)+DP/(HO*DPO)
      HS=1./A
      S=T-DT/2.
      RETURN
      END
$IBFTC ZP
C*******************************************************************
C**&&*PHYSICAL PROPERTIES OF WATER VAPOR*****
C&**&*&**&**&*******&***********&****&*********************************
      SUBROUTINE PP(T,DT,DEG,DEG1,XMUG,HV,CP)
      T=5.0*(T-32.0)/9.0+273.0
      CP=(7.7+.00045*T+.2521E-05*T**2.-.8587E-09*T**3.)/18.0
      T=T-273.0
      XMUG=(91.9+0.351*T)*.672E-07
      DEG=21493.61221632-400.15672832*T+2.5991631*T**2.-.00579602*T**3.
      DEG=62.43/DEG
      HV=2799.1422976-15.3096504*T+.20634452*T**2.-.00142704*T**3.
     /+.00000353*T**4.
      RS=HV*453.5924/1054.8
      T=9.0*T/5.0+32.0
      T1=5.0*((T+DT)-32.0)/9.0
      DEG1=21493.61221632-400.15672832*T1+2.5991631*T1**2.-.00579602*
     /T1**3.
      DEG1=62.43/DEG1
      RETURN
      END
$IBFTC ZL
C*****************************************************************
C*****WATER THERMAL CONDUCTIVITY*****
      SUBROUTINE KL(S,T,XKL)
      T=5.0*(T-32.0)/9.0
      XKL=587.*(1.+2.81*.001*(T-20.))
      XKL=XKL*2.389/4180.
      S=9.0*S/5.0+32.0
      RETURN
      END
```

```
£IBFTC MUL
C*****
C***&**WATER VISCOSITY****
C******&&****&*****************************************************
      SUBROUTINE MUL(S,T,XMUL)
      T=5.*(T-32.)/9.
      XMUL=1.996531-.0160284*T+.00006745*T**2
        XMUL=XMUL*.000672
      T=9.*T/5.+32.
      RETURN
      END
£IBFTC XDEL
C*****
C*****WATER DENSITY****
C*****
      SUBROUTINE XDEL(S,T,DEL)
      DEL=.97*62.43
      RETURN
      END
£IBFTC XCL
C**&**&&*****************************************************************
C*****WATER SPECIFIC HEAT*******
C*****
      SUBROUTINE XCL(S,T,CL)
      CL=1.0
      RETURN
      END
£IBFTC VPT
C*****
C*****PRESSURE-TEMPERATURE EQUATION FOR WATER****
C*****
C&*&**&&****8*****************************************************************
      SUBROUTINE VPT(P,T)
      P=P*760./(144.*14.7)
         IF(P.LT.30..AND.P.GT.5.) GO TO 2
      IF(P.LT.35..AND.P.GT.30.) GO TO 3
      IF(P.LT.90..AND.P.GT.35.) GO TO 4
      9F(P.LT.150..AND.P.GT.90.) GO TO 5
      IF(P.LT.230..AND.P.GT.150.) GO TO 6
      IF(P.LT.340..AND.P.GT.230.) GO TO 7
      IF(P.LT.520..AND.P.GT.340.) GO TO 8
      I6(P.LT.760..AND.P.GT=520.) GO TO 9
      IF(P.GT.760.) GO TO 10
    2 A=8.184254
      B=1791.3
      C=238.1
      GO TO 1
    3 A=8.139 986
      B=1767.262
      C=236.29
      GO TO 1
    4 A=8.0886767
      B=1739.301
      C=234.1
      GO TO 1
    5 A=8.0464202
```

```
      B=1715.429
      C=232.14
      GO TO 1
    6 A=8.0116295
      B=1695.167
      C=230.41
      GO TO 1
    7 A=7.9845588
      B=1678.948
      C=228.97
      GO TO 1
    8 A=7.9634288
      B=1665.924
      C=227.77
      GO TO 1
    9 A=7.948396
      B=1656.39
      C=226.86
      GO TO 1
   10 A=7.9186968
      B=1636.909
      C=224.92
    1 T=(B/(A-ALOG10(P)))-C
      T=9.*T/5.+32.
      P=P*144.*14.7/760.
      RETURN
      END
$ENTRY
 0.       0.5      0.147
-.068      178.93    129.03     0.0        1075.
```